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GAGE PLACEMENT STUDY

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Research and Technology Division
Air Force Systems Command
AIR FORCE WEAPONS LABORATORY
Kirtland Air Force Base
New Mexico

Project No. 1080, Task No. 108006

(Prepared under Contract AF 29(601)-5412
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Research and Technology Division
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2. REVIEW OF PREVIOUS EXPERIENCE

Principal technical reports and papers describing both field and laboratory studies involving measurements of soil stress, strain and "particle" motion (acceleration, velocity,and displacement) were reviewed. These studies ranged from investigations of soil stress and strains beneath moving vehicles to ground shock caused by nuclear blasts. The purpose of this review was to obtain information from previous experience regarding the effects of placement on the functioning of various types of gages in soil.

It was not possible to obtain much information on gage placement from these reports. In the earlier studies the significance of placement and other factors affecting gage response was not fully recognized and therefore little attention was given them. In the majority of nuclear field test programs there was little opportunity to study the factors influencing placement. The time schedule did not usually permit a thorough gage evaluation prior to the test and the limitation on the number of channels of instrumentation generally precluded duplicate measurements under different placement conditions. In many instances when it seemed likely that placement significantly influenced the gage response, sufficient detail describing the gages and the placement methods was not available to permit more than a qualitative evaluation. During the last few years the placement problem has been recognized, partly as a result of many unsatisfactory data, and a number of laboratory studies have been initiated to obtain more specific information.

Various methods of gage placement have been attempted. They generally fall into two categories: 1) recompacting soil around the gage, and 2) grouting. The observed test results do not show either method to be clearly better than the other, although the uncertainty of the results permits only an approximate comparison. The choice between grouting and recompacting is usually made for other reasons. For example, grouting is about the only reasonable placement method when the gages are located far beneath the soil surface in a bore hole. In addition, there is usually less uncertainty regarding the method of placement when grouting is used since descriptions of tamping procedures are often misleading and, there is sometimes doubt that the prescribed procedures are really followed by field crews.

Density discontinuity between the gage, the disturbed soil or grout immediately surrounding the gage, and the in situ soil have generally been considered an important factor influencing gage performance. Therefore, test procedures frequently prescribe that the in situ density be duplicated if possible by the grout or the recompacted soil. Attempts have even been made to match the dynamic modulus of the grout to that of the surrounding soil [1*]. Although grouting is usually considered easier to perform than soil compaction, some difficulty results from air entrapment in the grout causing cavities, and also from incomplete drying of the grout.

Another factor of great importance in field measurements, but one which usually cannot be altered, is the nonhomogenity of the soil in the test area. The question has been raised as to whether the discontinuity caused by the bore hole in the free-field could change the free-field ground motion to any great extent. Although it is expected that there is an effect, it is difficult to judge the extend from available test results. Discussions with persons associated with the field tests have revealed one case in which local conditions were thought to have been an important factor affecting gage registration. In this test, two instrumentation cannisters were placed in the same vicinity, one being in broken and fractured rock and the other in a more uniform rock. The results were so different that the conclusion arrived at was that the local rock conditions did have an effect on gage readings. Since little information on gage placement was found in the literature, the following discussion also includes a general summary of previous gage experience.

A. Stress Measurement

The basic problem involved in measuring stress in soil is that the gage will almost always have a "stiffness" different from that of the soil. This mismatch causes the gage to indicate a stress which is not the true stress, but rather one which is a function of the interaction between the soil and the gage. Of course for rapidly applied stresses such other problems as frequency response and density mismatch may also become significant. The error due to the soil-gage mismatch changes with a variation in either

* Superscript numbers cite references listed at the end of the text.

FOREWORD

This is the final report on Armour Research Foundation (ARF) Project No. K275, Gage Placement Study, sponsored by the Air Force Special Weapons Center, Kirtland Air Force Base, New Mexico, under contract AF 29(601)-5412. The work was performed during the period of July 1962 to May 1963.

Technical monitor on the program for AFSWC was Lt G. V. Bulin. Armour Research Foundation personnel who have contributed to the program include R. Arndt, R. Rusin, E. Selig, E. Stridde, and E. Vey.

ABSTRACT

A study has been made of the various factors which affect the behavior of gages in soil. The ultimate objective of the study is to provide guides and recommended procedures for gage placement. Previous field and laboratory experience with stress, strain and motion measurement in soil has been reviewed and a list of references provided. This was supplemented by an experimental investigation of embedded accelerometers to determine the importance of gage density and placement procedures on gage response.

The most important factors influencing motion measurement appear to be (1) gage density in relation to the soil, and (2) placement conditions. Reproducibility of peak acceleration measurements was within ± 15 percent on the average. For a variation in accelerometer density of 55 percent, a 12 percent difference in peak accelerations was observed for pendulum tests in sand and a 37 percent difference for shock tube tests in clay. Changing the static compaction pressures for placement of gages in clay from 12 psi to 42 psi resulted in a decrease of 22 percent in the peak accelerations recorded.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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I. INTRODUCTION

While the physical concept of stress, strain and acceleration measurement in a soil mass is understood, many experimental difficulties are encountered in measuring them correctly. These generally are related to 1) gage design, 2) gage placement, and 3) instrumentation. The principal emphasis in this study is on the second, although placement cannot be considered independently of the other two. For example, the type of transducer may affect gage design; and gage design, in turn, may place certain requirements on placement or even dictate placement methods. Also, some field placement methods are more suitable than others, and these considerations may place limitations on gage design. In general, the problems are not so severe in the laboratory because of the greater flexibility of operation and because an entire soil specimen is usually recompacted for the test.

The purpose of this study is to develop guides and recommended procedures for the placement of gages in soil. Primary interest is in field applications although many of the considerations are equally pertinent to laboratory studies. Interest in field measurements of stress, strain and acceleration in soil has increased greatly in recent decades because of the nuclear weapons test programs. However, such measurements, especially stress, have been recorded in connection with a variety of studies and construction projects for a much longer period. Examples are pressures beneath roadways, in dams, on underground tunnels and against retaining walls. Many problems are now being investigated in the laboratory where these quantities must also be measured.

A complete consideration of all types of gages is beyond the scope of this study. Previously most attention has been given to stress gages although the problem of properly measuring stress has by no means been solved. In recent years the interest in particle motion (acceleration, velocity, and displacement) has greatly increased, partly due to the difficulty in measuring stress. Because the least amount of data has been obtained on the problems of measuring soil motions, the emphasis in the experimental part of this study has been directed toward these measurements.

The study has been divided into three principal phases: 1) a review of previous experience in soil measurements as reported in the literature, 2) laboratory investigation of the factors influencing accelerometer response and 3) preparation of recommendations for gage placement supplemented by conclusions regarding the factors influencing gage response.

the soil or gage stiffness, or with a variation in the thickness-to-diameter (T/D) ratio of gage. It is logical then to expect that the conditions of the soil immediately surrounding the gage which are created during placement also have a significant effect on stress gage response.

In a fundamental study of earth pressure cells, Peattie and Sparrow[2] considered 1) T/D ratio of the cell, 2) ratio of pressure sensitive area to total gage face area, and 3) ratio of gage stiffness to soil stiffness. Effect of placement was evaluated in the following manner: the container was filled with soil to the level at which the gages were to be located, and the surface made flat. Six identical gages, all stiffer than the soil were used. Two gages were placed directly on the soil surface, two pressed into the soil a distance equal to one-half of the gage thickness, and two pressed into the soil a distance equal to their entire thickness. The remainder of the soil was added to complete filling the container and then the surface pressurized uniformly. The response of the gages pressed in to their entire thickness was approximately 15 percent greater than that of the other gages. The exact condition of the soil was not indicated for these tests, but it appears that an increase in soil density across the face of the gage increased the stress concentration in the vicinity of the gage, thereby increasing gage response.

The following additional conclusions were made in the report:

1. The effect of change in T/D ratio was found to be significant. For a particular gage of constant stiffness and diameter, an increase in T/D ratio from 0.2 to 1.0 caused an increase in cell registration ranging from 28 to 62 percent under the same loading conditions in several soils.

2. Since the stress is not uniformly distributed over the face of the gage, being higher at the edge than at the center, the overregistration was found to decrease as the sensitive area was decreased in proportion to the total gage area.

3. When the stiffness ratio (ratio of gage stiffness to soil stiffness) was unity, the gage indicated the true stress, but the rate of change of the over-registration was greatest, i.e., a given change in stiff-

ness ratio produced the greatest change in over-registration for values of the ratio near unity.

A review of gages designed to measure static earth pressures has been compiled in reference 3. The principal cells which have been used for measuring pressure in earth masses, as distinguished from those designed for use on the face of a buried structure, include the Goldbeck cell, the Waterways Experiment Station (WES) cell, the Swedish State Power Board cell, the Road Research Lab acoustic gage and the Plantema cell. No information on the effects of placement is given.

The Waterways Experiment Station has reported experience gained in the measurement of stresses in soil beneath applied surface loads [4, 5, 6]. The first series [5] was conducted in a compacted bed of clayey silt (remolded Vicksburg weathered loess with a plasticity index of 12) using 12-in. diam WES earth pressure cells. The soil was first rolled to a depth of about 1 ft above the level at which the cells were to be located. A hole was then dug for each gage and the bottom of the hole sloped to orient the gage at the desired angle. The sensitive face of the gage was placed in contact with the bottom of the hole and the soil replaced by hand-tamping with sufficient effort to provide a density approximately equal to that of the compacted fill. Loads were applied to the soil surface through bearing plates and stress readings taken with the embedded cells using calibrations obtained under uniform fluid pressure. A check of the gage performance was obtained by comparing the measured stresses with those computed from the theory of elasticity and by checking stress equilibrium within the soil. With this method of comparison, which provides only an approximate check as a basis, it was reported that the gages read definitely within about ± 25 percent of the expected reading and probably within ± 10 percent, with no apparent over- or under-registration as a whole. However, the data given in the reference show scatter greater than 25 percent in some cases. Although it is not possible to be certain how much of this effect is due to placement, on the assumption that the apparent error is randomly distributed about the expected value with no apparent over-registration, the variation due to placement is probably of the same order as the total variation, i.e., ± 25 percent.

The WES studies were extended to compacted sand fills[4] using improved WES earth pressure cells and newly developed shear cells. Again, the soil was compacted to a height above the cell locations and then holes dug to position the gages. The sand was carefully replaced around the gages to match the density of the rest of the fill. Gage response due to applied surface loads was measured and, based upon a comparison with expected stresses, information on the reproducibility and consistency of gage performance was obtained.

Reproducibility as used in reference 4 is interpreted to mean the percent (±) variation of the pressure readings from the average for each individual gage upon successive identical loadings without removing and re-embedding the gage. Reproducibility would therefore indicate the change in soil-gage interaction upon repeated loading. The results given in Table 1 show a reproducibility of about ±5 percent based upon 99 percent of the data for the pressure and shear cells.

TABLE 1

REPRODUCIBILITY OF SOIL GAGES[4]

Type of Gage	Reproducibility as Percent of Average Reading 50% of Data	 99% of Data	Number of Readings
Pressure Cell	± 1.5	± 5.6	700
Shear Cell	± 1.1	± 4.2	640
Deflection Gage	± 1.5 (high deflection)	± 5.8	500
	± 4.0 (low deflection)	± 15.2	300
Strain Gage	± 10.9	± 41.6	290

As used in reference 4, consistency refers to the correlation of the readings between identical gages with equivalent installations, i.e., at positions where the stress conditions should be the same. Consistency results listed in Table 2 are given in terms of the percent (±) deviation of the gage readings from the average values under identical conditions. The consistency of readings for the pressure cells was ± 11.9 percent compared to a reproducibility of ± 5.6 percent. The difference between these two values should give an indication of the minimum variation due to placement. Depending upon how the results are interpreted, on the average the variation due to placement ranged from ± 6 to ± 12 percent.

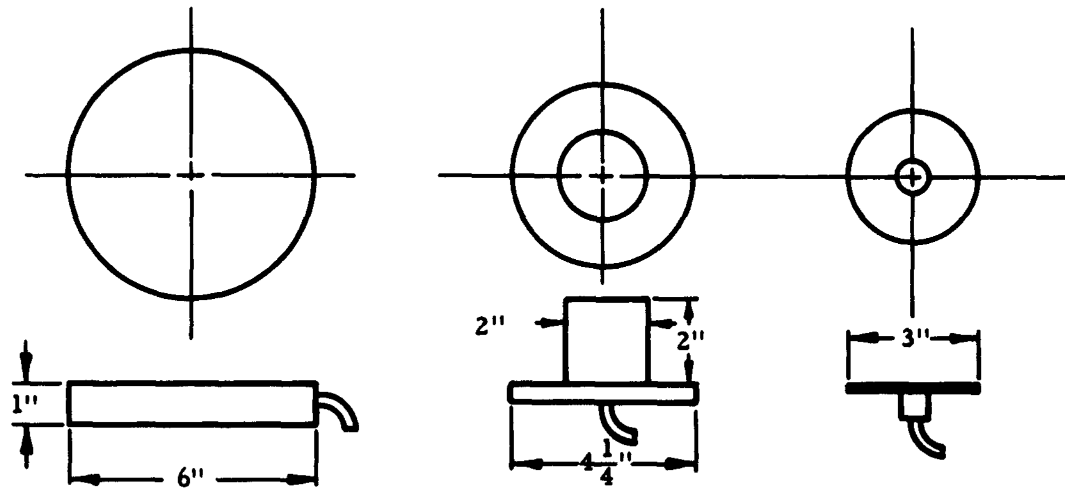
TABLE 2

CONSISTENCY OF SOIL GAGES [4]

Type of Gage	Consistency as Percent of Average Reading		Number of Readings
	50% of Data	99% of Data	
Pressure Cell	± 3.1	± 11.9	40
Deflection Gages	± 9.5	± 36.3	13

In this case, neither consistency nor reproducibility necessarily indicates the accuracy of the stress readings. In the vicinity of the surface load measured, the vertical stresses were higher than given by the elasticity theory and the horizontal stresses were lower; however, this may be expected because of the difference in behavior between the sand and an elastic material. If over-registration is assumed to be only a few percent, then the accuracy of the stress readings should be about the same as the consistency, i.e., ± 12 percent.

In the third series of WES tests [6], surface loads were produced by a moving vehicle on compacted clay. Three types of cells were used in these tests: 1) WES earth pressure cell, 2) WES fluid pressure cell, and 3) a gage constructed from a Consolidated Electronics Corporation (CEC) pressure transducer. The geometry of these gages is shown in Figure 1.



(a) WES Earth Pressure Cell

(b) WES Fluid Pressure Cell

(c) CEC Cell

Fig. 1 STRESS GAGES FOR WES TESTS [6]

The clay fill was first compacted with rollers and then gage holes about 7 in. in diameter were dug to the required depth. The soil was re-compacted by hand around the gages to the same strength as the surrounding fill. A penetrometer was used to control the compactive effort.

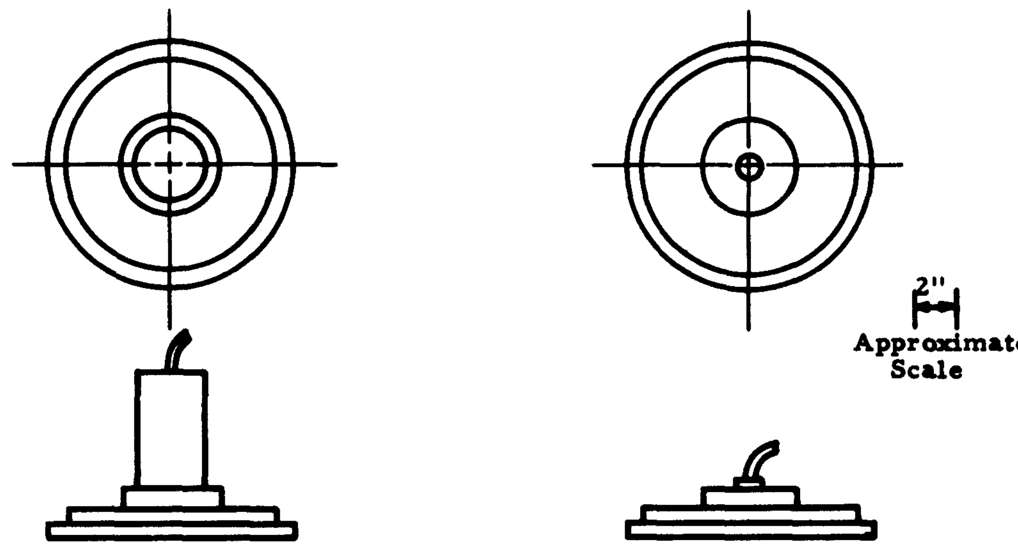
In the firm clay fill several of the gages read very low stress for the first pass or two, but increased thereafter, suggesting that the soil had not been compacted sufficiently around the gage initially. In the softer clay fills it appeared that placement was better since the readings were more consistent, but rutting beneath the vehicle caused considerably more movement of the gages than in the firm clay. The poorest results were obtained with the fluid pressure cells. Generally these cells recorded stresses too low and were difficult to place properly because of their shape. The fact they read low values of stress suggests that they have not been seated properly because their stiffness and high effective T/D ratio would tend to cause readings which are too high. The experience with the CEC cell was similar. One of the shortcomings of this cell is its very small sensitive area which would make it especially sensitive to placement and soil irregularities.

Studies involving the measurement of stresses in noncohesive soil masses subjected to vibratory loads have been conducted by Bernhard[7]. The problem of measuring low amplitude vibratory stresses in soil appears to be less difficult than other types of soil stress measurement. This is primarily because under continued vibration the soil approaches a state of elastic equilibrium so that there is no further change in soil-gage interaction and discontinuities and variation in placement conditions tend to be smoothed out.

In placing the gage, as little sand as possible was removed and it was replaced to the same density using a penetrometer as a means of checking. The accuracy of the stress measurements was determined by correlation of the experimental and theoretical results assuming that the soil behaved elastically during vibration. On the basis of this analysis it was reported that 68 percent of the readings were within $\pm$ 5.2 percent of theoretical and 95 percent within $\pm$ 10.2 percent.

Attempts have been made to measure the stresses in soil produced by nuclear blasts in conjunction with a number of the nuclear weapons test programs. A description of the principal types of gages used and an indication of some of the problems encountered is given in reference 8.

The Carlson-Wiancko earth pressure cell is reported to be one of the most successful used in any of the field tests. It is a diaphragm type gage in which the deflection of the diaphragm is measured by a variable reluctance transducer and calibrated in terms of a uniformly applied pressure. The gage is basically disk-shaped, but as originally used in the Buster-Jangle and Tumbler-Snapper[9] series, there was a large protrusion on the back of the gage to house the transducer (Figure 2). The reliability of the gage was demonstrated in these tests, but the recorded stresses appeared higher than expected. It was thought that the transducer housing caused a stress concentration around the gage, hence, the housing was made more compact prior to further use. The modified Carlson-Wiancko cell was used in the Upshot-Knothole series [10] and better results were reported. However, insufficient information was given to evaluate the effects of placement.



(a) Original

(b) Modified

Fig. 2 CARLSON-WIANCKO EARTH PRESSURE CELLS

For measurements in rock or hard soils the gages are generally grouted into a prepared hole. Some attempts have been made to use grouts which match the earth as closely as possible [11]. For other soil conditions the gages are generally mounted flush with the bottom or sides of the prepared holes. Moistened and screened soil is then carefully tamped around the gage either mechanically or by hand.

In the last five years there has been an increasing interest in the development of laboratory and field gages for improved measurement of shock-induced stresses in soil. In one report [12] on the development of a gage for field use the following considerations were indicated as important in stress gage design: 1) relative stiffness between the gage and the soil, 2) gage density, 3) acoustic impedance (density times velocity), and

4) placement. It was concluded that the acoustic impedance and density of the gage should be matched to that of the soil and the soil placed around the gage should be recompacted to the same condition as the rest of the fill. It was pointed out that the Carlson-Wiancko gage is stiffer and denser than the soil, and has a higher acoustic impedance; therefore, in general, this gage should over-register unless the placement conditions compensate.

The gage developed in this study consisted of two sections each with a disk attached to a hollow stem, one sliding within the other (Figure 3). The stem houses the transducer and the pressure sensitive element is located in the face of one of the disks. Transducers were also added to permit measurements of strain and acceleration.

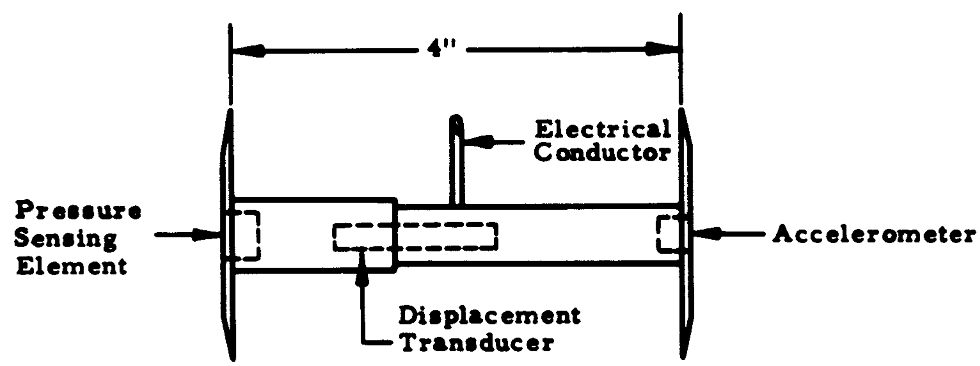


Fig. 3 SOIL-FILLED STRESS GAGE

Placement of this gage is not accomplished as easily as with other stress gages, especially in cohesive soils, because of the difficulty in compacting the soil around the stem between the two end disks. Satisfactory performance of this gage was reported in confined specimens of dry sand although significant variations in results which appeared to be due to lack of adequate control of the sand density were noticed. The scatter was especially significant at high stress levels and under dynamic loading.

Small disk-shaped piezoelectric stress gages (1/2-in. diam by 1/32-in. thick) have been developed at United Research Services[13] to measure dynamic stresses in a confined column of sand. Preliminary studies of these gages in sand indicate that the over-registration is small so that uniform pressure calibrations may be used to compute stress. The total range of data scatter including the effects of placement is thought to be about $\pm$20 percent. The uncertainty arises because, as a result of attenuation of stress along the length of the column, only the stress at the sand boundary is accurately known. Gage placement was accomplished by pressing lightly on the gages to seat them on a leveled cross section of sand at the desired depth before additional sand was added.

An extensive investigation of soil stress measurement has been made at Illinois Institute of Technology in connection with a study of wave propagation in sand.[14] The gages developed in the study all utilized the piezoelectric transducer as a sensing element. However, a number of variations in the T/D ratio and means of encasing of the gage were considered.

It was observed that the gage response is linear when the soil stress-strain relationship is linear. Thus, a change in the soil stiffness has an appreciable effect on the gage response whether caused by a change in confining pressure, density or by the normal stress level. This is true even though the gage stiffness itself is very high compared with that of the soil.

Placement is another significant factor which affects gage response and can account for the significant variation in the response even though all other conditions are constant. Variations of up to plus or minus 50 percent were observed due to placement. With careful techniques it is possible to hold variations due to placement within $\pm$10 percent.

B. Strain Measurement

The use of free-field strain gages in test series Tumbler-Snapper, Upshot-Knothole, Teapot, Plumbbob and Hardtack-II have been reported[8, 15, 16, 18], but, on the whole, unsatisfactory results were obtained because of instrumentation difficulties. In the majority of studies in which strains in soil have been measured, the principal disadvantage of the gages is the physical connection required between the gage points. This causes disturbance of the soil in the region between these gage points and complicates the placement of soil around the gage. It is generally considered that a suitable strain gage should meet the following requirements[8, 17]: 1) there should be a satisfactory means of attaching to the soil, and 2) it should freely follow the soil movement which means, in part, that the stiffness of the gage should be as small as possible and the density of the gage should be about the same as that of the soil.

For those tests in which the strain measurements have been made in rock generally wire resistance strain gages have been embedded in cast cement cylinders[18] or on the surface of rock cores taken from the parent material. The cores are then grouted into drilled holes in the rock.

The general procedure used for placement of short-span strain gages in prepared holes in soils, other than by grouting, involves recompacting the soil. Moistened and screened soil similar to that removed from the hole is supposed to be carefully hand-tamped around the gage for a depth of about one foot above the gage.[8] The remainder of the fill is usually tamped mechanically.

Measurements of soil strains and displacements have been made at WES in connection with the previously described studies of stresses in soil due to applied surface loads.[4] Selsyn motor-type gages were constructed for measuring the relative movement between points on the surface and points in the soil at various depths. The strain gages used were developed by the Ohio River Division Laboratories. The core of a linear differential transformer was attached to one end of a rod and a circular disk to the other. A second disk was centered on the transformer coil. The assembled gage had a base length of 10 in. These gages were used only in sand. The method of placement is basically the same as used for stress gages.

The reproducibility and consistency of the readings obtained with the strain and displacement gages are given in Tables 1 and 2. Neither the strain nor deflection gages performed as well as the pressure and shear cells. It was suggested in the discussion of the stress gage results that the errors due to placement are probably on the order of the difference between consistency and reproducibility. A comparison of Tables 1 and 2 shows that, for each case represented, the consistency is about twice reproducibility, hence the errors due to placement may be about the same magnitude as the reproducibility. Thus, for the strain and displacement gages the placement effects would be about $\pm$ 42 percent and $\pm$ 15 percent respectively. The considerable effect, especially pronounced for the strain gages, may be the result of the relatively small values of strain which occur in a compacted sand fill.

Field tests in which strains were measured in the soil produced by static surface loads and by vehicles moving over the ground surface have been conducted at IIT Research Institute.[19] The gages developed for this study used miniature iron-core differential transformers. They were specially designed for embedding in natural soil with as little disturbance as possible. Two configurations were used (Figure 4), one for vertical orientation and the other for horizontal orientation, the difference being required by the method of placement. Each end of the gage for vertical displacements was coupled to the soil by an auger which was screwed into a pilot hole drilled into the soil. The ends of the horizontal gage were coupled to the soil by stakes which were pressed into the bottom of a narrow vertical slot cut into the soil. In some tests, after the gages were placed, the holes were backfilled with soil compacted to the same penetration resistance. In other tests the holes were left unfilled.

The response of two gages as a function of static surface pressure is given in Figure 5. The horizontal gage did not begin responding to the load immediately, indicating some small slack in the coupling. It is very difficult to place these gages in soil, especially the horizontal gages, such that slack in the system is less than a few ten thousandths of an inch. The nonrecovery of the displacement upon unloading, shown in Figure 5, is believed entirely a function of the soil hysteresis.

A comparison of the response of sets of gages located in identical positions with respect to the load showed an average variation of $\pm$ 23 percent. These values, termed consistency in the WES tests, primarily reflect both

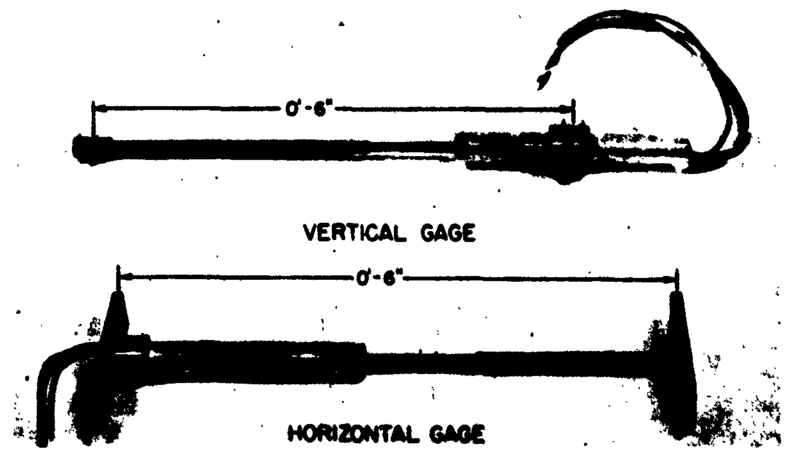


Fig. 4 ARF COUPLED STRAIN GAGE

the effect of placement and the nonhomogenieties in the soil. However, it is expected that an appreciable part of this is due to placement. Within this data variation no differences were observed between the condition where the gage holes were backfilled and where they were not.

C. Soil Motion Measurements

Until recently very few controlled experiments to study the response of embedded gages for measuring soil motion, i.e., acceleration, velocity and displacement have been conducted. Thus, information about the factors affecting behavior of these gages is largely qualitative. It is generally believed that matching the density of the gage and the grout to that of the in situ soil is important if the gage is to reliably follow the soil motion. It is also considered important to make the seismic impedance (density times wave velocity) match that of the in situ soil unless the dimensions of the grouted region are small compared to the wave length of the pulse. However, placement conditions, including stiffness of the disturbed region, must also be important, e.g., a soft region around the gage may permit the inertia of the gage to cause a lag in response.

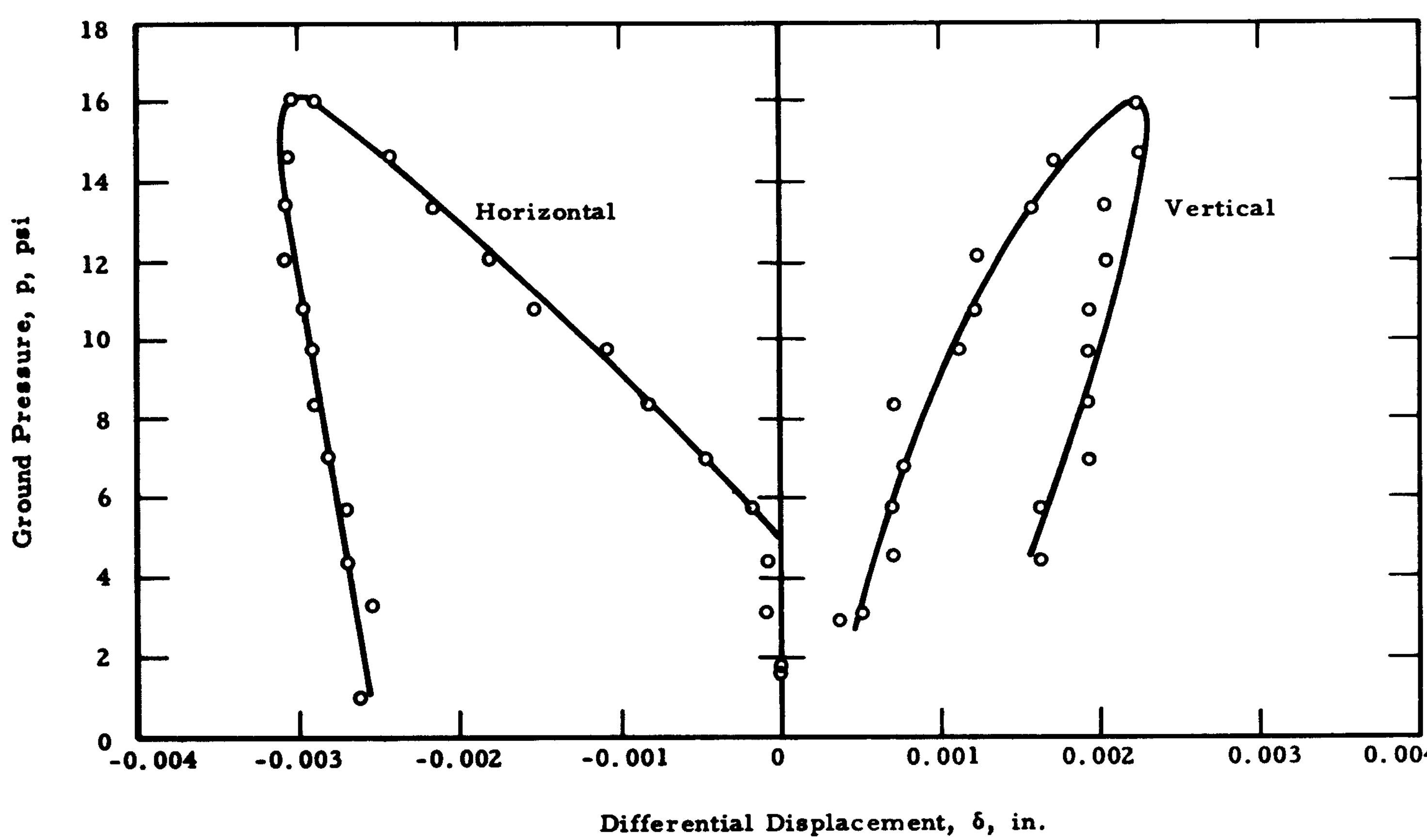


Fig. 5 **REPRESENTATIVE STRAIN GAGE DISPLACEMENT RESPONSE IN SILTY CLAY**

Ground motion measurements in connection with nuclear field tests began as early as Operation Greenhouse and have been included in nearly every major test series since then[8]. Initially most of the gages used were accelerometers because available velocity gages had poor frequency response or were too complex and expensive. Velocity and displacement information was obtained from the acceleration records by direct integration. Often correlation of the integrated values with directly measured velocity and displacement has been poor. Elaborate base line corrections have sometimes been introduced into the integration to improve results, but, in general, it has been found that integration, at least when done numerically from the printed records, is not satisfactory for obtaining velocity and displacement. This is, in part, because the typical acceleration pulse is composed of a large-amplitude short-duration pulse followed by small amplitude oscillations which are difficult to resolve accurately but which can have a large effect on peak velocity or displacement. A description of most of the gages which have been used for motion measurement is given in reference 8.

In recent years the interest in ground motion measurements for nuclear field tests has shifted from acceleration to velocity. The reasons for this change in emphasis appear to be the following: 1) velocity is associated with energy level and is useful in correlating with phenomona such as structural damage, 2) velocity scales well, and 3) velocity changes less abruptly than acceleration, hence measurements should be less affected by placement conditions and density mismatch. Some investigators believe that maximum confidence can be placed in peak displacement measurements. The reason given is that displacements change less rapidly than accelerations and hence the peak values are less affected by the time variation of particle motion preceding the peak displacement. For example, the gage may lag the time motion initially, but eventually it will catch up and perhaps even lead the soil motion. It is likely that in this case the peak displacement will be much less in error than the peak acceleration which occurs when the motion is first induced.

Piezoelectric accelerometers were used in Project Cowboy[20] to permit high frequency acceleration measurements. The cannisters carrying the gages were placed with a grout matching the properties of the in situ material.

In Operation Tumbler[21] two different methods of installation of the ERA accelerometers were tried. The gages were mounted in the bottom of holes 5 ft below ground surface on a cube of concrete which was grouted into the undisturbed soil. One hole was filled with loose sand; the others were cased and filled with sand bags. However, because burst heights and bomb yields were different, no conclusions regarding the effect of these two placement methods on gage registration could be drawn from the data. Since the accelerometers were attached rigidly to the undisturbed soil, the gage response to ground transmitted shock may not have differed for the two types of backfill conditions. However, a difference may have been expected in the measured acceleration caused by the overpressure transmitting a downward acceleration to the gages.

Efforts have also been devoted to the development of gages for measuring transient displacement directly. Sandia, BRL and SRI have been the principal participants.[8] Although little information on the effects of placement is reported, it is generally believed that large displacements are the easiest of the ground motions to measure from a placement point of view.

Simultaneously with the laboratory studies being conducted at IITRI other investigations on embedded accelerometer behavior were in progress at Stanford Research Institute.[24] The purpose of their study was to determine, if possible, the discrepancy between recorded acceleration and soil acceleration and to find the optimum accelerometer configuration for determining soil motion. Miniature Endevco accelerometers were encased in a variety of metal and plexiglass caps to provide a range of aspect ratios and densities. The gages were embedded in dry sand and subjected to a pressure pulse with about one millisecond rise.

Details of placement were found to have the greatest affect on peak acceleration. Considerable variation in peak acceleration was observed for supposedly identical tests. However, there was much less variation of the peak velocities obtained by integrating these acceleration records. Within the reproducibility of the results no trends with respect to gage density or aspect ratio were observed.

3. LABORATORY STUDY

Numerous factors influencing the performance of embedded gages have been discussed in the preceding chapter. It is evident that, on the whole, available information is insufficient for an evaluation of the significance of these factors. The most pressing need appears to be related to accelerometers where a qualitative evaluation must at present be largely based upon intuition.

To provide a sounder basis for recommendations regarding the placement of accelerometers, a series of laboratory experiments were conducted as part of this study. Consideration of all factors expected to influence accelerometers was not possible within the limit of available time and funding. Therefore, attention was concentrated on two aspects 1) variation of gage density with respect to soil density, and 2) placement conditions, including soil compaction and grouting. The two soil types used were a uniform dry Ottawa sand (90 percent between 20 and 40 mesh) and a compacted plastic clay (liquid limit = 63, plasticity index = 31, principal clay mineral = kaolinite). Some attention was given to the configuration of the embedded gage.

A. Apparatus and Test Procedure

Basically, two experimental facilities were involved. The first, a pendulum apparatus, utilized hydrostatically confined cylinders of sand having properties which could be accurately controlled and reproduced. This apparatus was used to evaluate 1) gage reproducibility, 2) the effects of gage density, 3) controlled variation in soil properties, and 4) gage configuration. The second facility, a rigid chamber filled with clay and loaded by an air shock tube, permitted an evaluation of 1) gage response under shock loading, 2) the effects of placement conditions, and 3) gage density.

1. Pendulum Apparatus Experiments

The pendulum apparatus (Figure 6) is a simple device for applying controlled impact loads to small cylinders of sand confined by means of an internal vacuum. The two pendulums are steel cylinders of approximately equal size and weight. An accelerometer is attached to each pendulum to measure motion during impact. The sand specimen is encased in a rubber membrane and attached to the reaction pendulum by means of the confining vacuum. The second pendulum is used to impact the specimen. The specimen density, confining pressure, and impact velocity may be varied to give a range of test conditions.

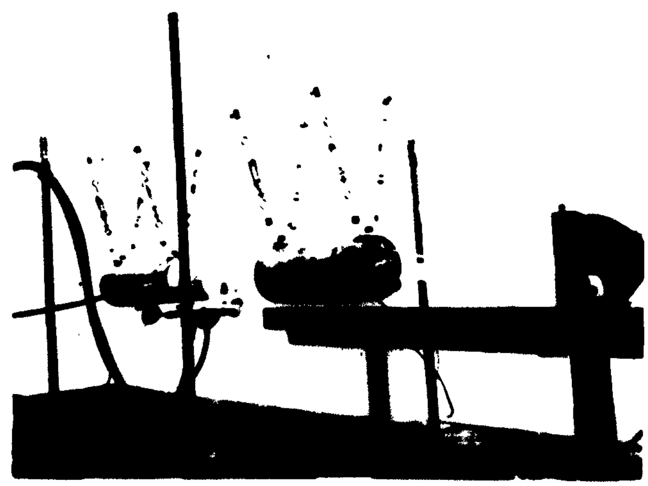


Fig. 6 PENDULUM APPARATUS

The sand specimen was prepared on the reaction pendulum using a mold split longitudinally and through the cross section at which the embedded accelerometer was to be located. The mold was first filled to this cross section either by vibrating the sand with a Vibrotool or by pouring the sand from a prescribed height. The gage was set in place on the leveled sand surface, the remainder of the specimen was formed. A diagram of the specimen with the gage in position is shown in Figure 7. The specimen is 4 in. in length and about 3 in. in diameter. One end of the embedded accelerometer

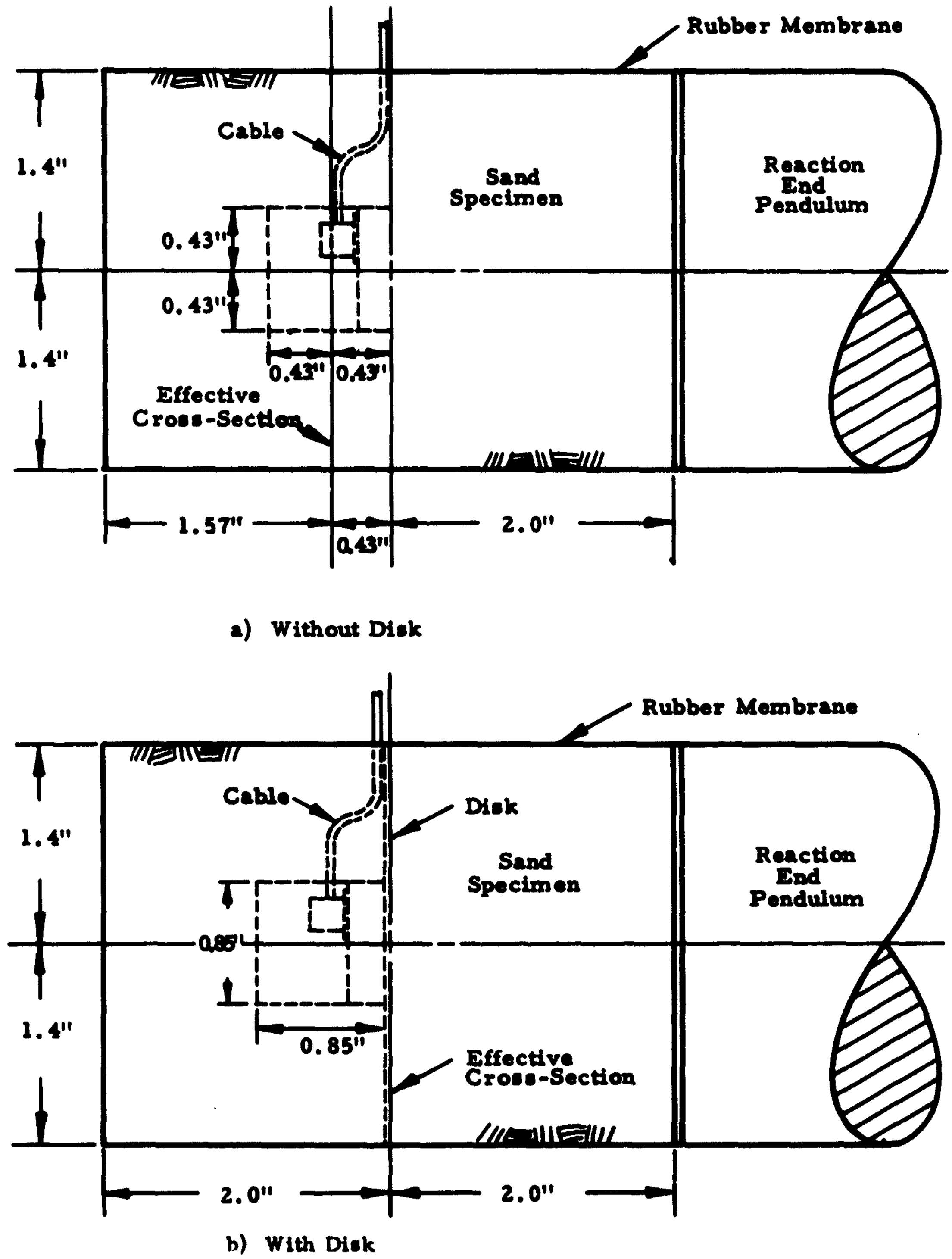


Fig. 7 LOCATION OF ACCELEROMETERS IN PENDULUM SPECIMEN

is coincident with the center cross section of the specimen. Since the rubber membrane was also split at this cross section, the electrical conductors from the gage exited from the specimen at this point.

Specimen densities ranged from 99 pcf to 112 pcf (approximately 15 percent and 90 percent relative density, respectively). Although the percent increase in soil density from minimum to maximum is small, the corresponding change in stiffness as well as soil strength is significant. The effects of density mismatch should be more pronounced at the lowest sand densities; therefore, most of the pendulum tests were conducted with the sand in the low relative density condition.

An attempt was made to obtain an independent measure of the acceleration of the specimen cross section on which the gage was located. The method employed was to photograph the specimen during impact with a high-speed 16mm framing camera (4000 frames/second). Fine lines were drawn on the membrane surrounding the specimen at 1/4-in. intervals along the length to provide a number of measurements in the region of the gage and to ensure that at least one line would represent the cross section near the center of the gage. Values of displacement obtained from the film records were to be compared to the values obtained by double integration of the embedded accelerometer records. This approach is recognized as not altogether satisfactory because of uncertainties in integration and resolution of the film records, but no other method is available.

Difficulty with the camera timing lights and the oscilloscope syncronization signal made the first films incomplete and no quantitative information could be obtained. However, it was observed that resolution of the lines photographed on the specimen was not good enough to provide an accurate measure of the displacement of the cross section as a function of time. Unless displacements can be accurately determined they will not distinguish small variations in acceleration response. After elimination of the timing problems and improvement of the resolution, additional film records were made for analysis. Both an optical comparator and a cathatometer were used to obtain the data from the films. The inconsistencies and scatter were still too great for the method to be of any value. It is expected that the photographic method could be improved by further development, although perhaps not enough to be useful. However, the time and cost involved made further efforts in this direction beyond the scope of the study.

Some thought was given to using a transparent rubber-like material in place of the sand for observing the embedded accelerometer response. The gage would be embedded in the center of a rubber cylinder and subjected to the same series of impacts in the pendulum apparatus. High speed photographs would be used to simultaneously observe the motion of the gage and lines on the surface of the specimen. It was hoped that these tests would show any variation between the motion of the embedded gage and the cross section of the specimen. Although a material suitable for this purpose was developed by the Chemical Engineering Section, these tests were postponed and subsequently canceled in favor of additional shock tube tests.

2. <u>Shock Tube Apparatus Experiments</u>

The shock tube apparatus (Figure 8, 10) provided a method of studying air shock induced accelerations under conditions more nearly simulating those in the field. A laterally constrained specimen of clay was used and the accelerometer compacted or grouted into a hole bored in the soil. The clay was contained in a glass-sided box 24 in. deep, 24 in. long, and 4 in. wide. To facilitate a comparison of results the same specimen was used for all of the tests and subjected to an identical loading for a variety of gage density and placement conditions.

Shock pressures of up to 6.5 psi were provided by using the bursting diaphragm method. Rise time of the air shock was essentially zero, duration of the peak pressure about 5 msec and total pulse duration about 15 msec.

Compaction of the clay was carried out with the specimen on its side so that any layering would be parallel to the two-dimensional plane of wave propagation. The standard proctor hammer was used with sufficient number of blows per layer to cover the surface twice. The 4 in. thickness was completed with 5 layers. The initial moisture content of the clay was 32 percent and the average soil density 115 pcf. This was maintained throughout the tests by covering all exposed soil surfaces with plastic wrap. An unconfined compressive strength of 2-1/4 tons per sq ft (or bearing capacity) was measured with a pocket penetrometer.

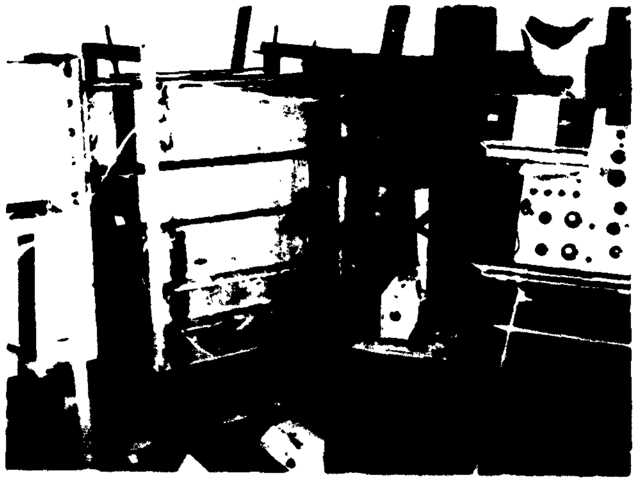


Fig. 8 APPARATUS FOR SHOCK TUBE EXPERIMENTS

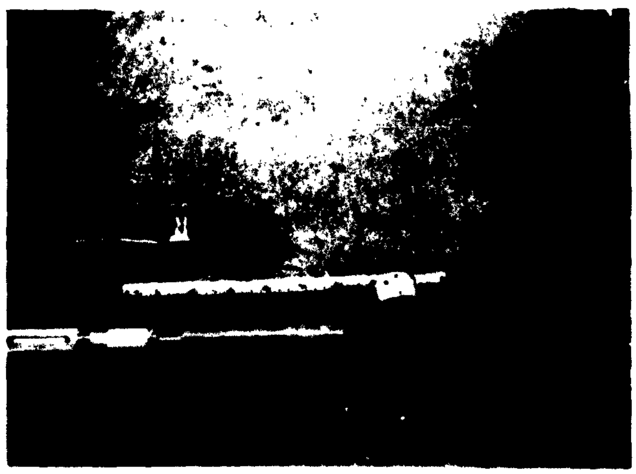


Fig. 9 PREPARATION FOR PLACEMENT OF GAGES IN CLAY

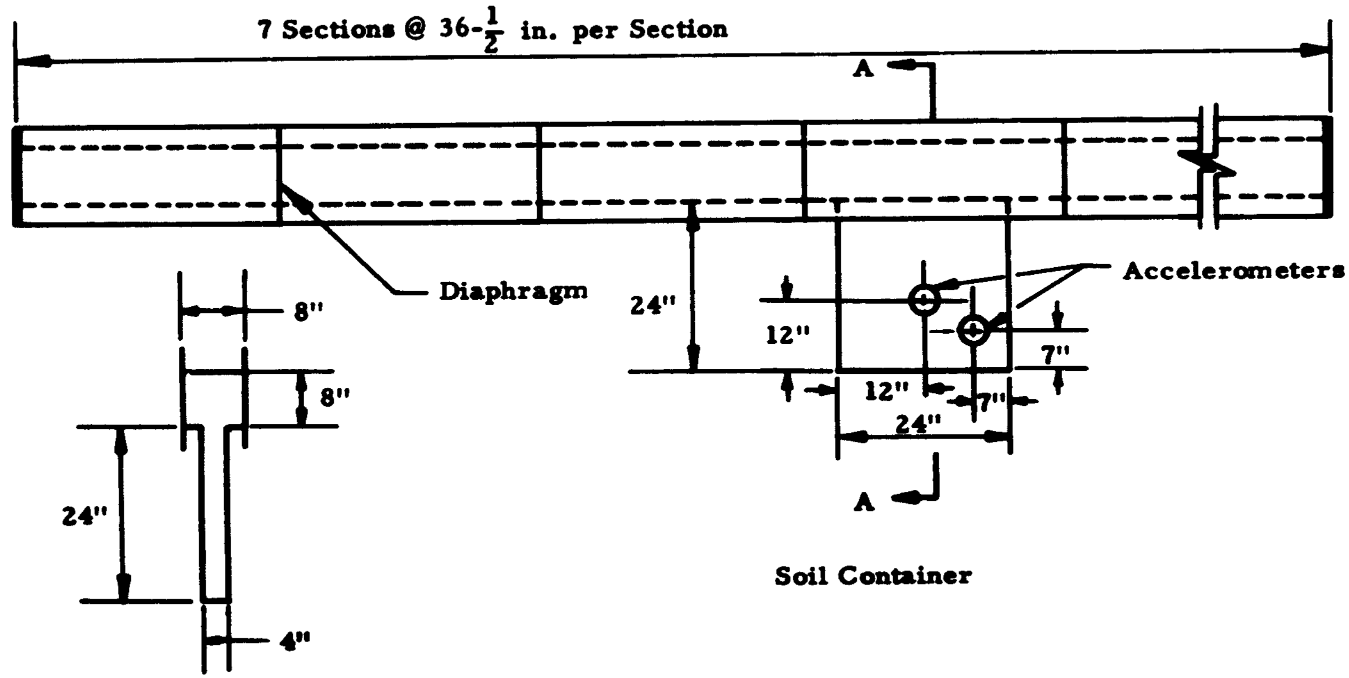


Fig. 10 SCHEMATIC OF SHOCK TUBE APPARATUS

With the glass side removed the hole for the gage was made in the center of the specimen (parallel to the 4-in. direction) using a 2-in. diam. thin-wall tube. The hole extended from the front surface to the back, i.e., the entire 4 in. The material removed was broken into finer pieces for ease in replacing around the gage.

Three methods of placement were used:

1. Soil was compacted around gage with a compaction pressure of 42 psi.
2. Soil was compacted around gage with a compaction pressure of 12 psi.
3. Gage was grouted in place with a plaster-of-paris compound ($CaSO_4$).

The bore hole was filled approximately half way using clay with the desired compaction effort,or using grout. The gage was positioned, and soil carefully compacted around it with same effort. Then the remainder of the hole was filled and the front glass put into place. The bore hole with gage and compacting device is shown in Figure 10. The compaction device is a pocket penetrometer with an extension which has a diameter of 0.875 in. When compacting in the narrow space around the gage, the extension was removed and a correspondingly lower scale deflection was used to adjust for area differences. With the minimum compactive effort, (11.6 psi) it was necessary to break up the soil into fine particles. This was accomplished by using a number 10-mesh sieve and grating the soil through it. As an independent check on the soil and loading conditions and for standardization purposes, another accelerometer, also shown in Figure 9 was placed in the lower left hand corner of the box (see Figure 10). However, because of problems with moisture and pressure sensitivity, the data obtained with this gage were unreliable; thus this reference gage was eliminated after a series of experiments.

B. Accelerometer Development

The selection of accelerometer for the experimental study was dictated primarily by size, but also by method of cable attachment and frequency response range. To provide for a variation in density and configuration it was decided to enclose a small piezoelectric accelerometer within a machined case with a maximum dimension of 1 in. Because of this size limitation, which is imposed by the pendulum specimen, a subminiature model was selected*. Its natural frequency (105 kc) was ample for high frequency response; the low frequency response was provided by using a Kistler Charge Amplifier** in the circuit between the accelerometer and the recording oscilloscope. The electrical cable is attached at the side of the gage thus permitting it to be placed in the soil in the plane of the motion to minimize cable restraint on accelerometer response. The shape of the accelerometer permits a case design with a T/D ratio of one or less.

The first design for the accelerometer case had an overall height and diameter of 0.75 in. Each case was made up of a base, cap, and thin wall and was held together by three brass screws extending from the top cap to the base (Figure 11). Since the effects of mismatch between average gage density and soil density was one of the objectives of this investigation, two cases were constructed. Aluminum was used in the entire structure of one case, the second case used an aluminum base with a steel wall and steel cap. The average densities obtained using these designs were 110 pcf and 165 pcf, respectively. Based upon an average specimen density of 105 pcf, the ratios of gage density to soil density were thus 1.05 and 1.57, i.e., about the same as the soil and about 60 percent greater. The performance of the accelerometer was evaluated using the pendulum apparatus since this method provides a high degree of reproducibility.

It was originally thought that a comparison of the records of the embedded accelerometer with those of the two pendulum accelerometers would provide a means of evaluating the shape and magnitude of the embedded gage response. An analysis of expected acceleration of various soil cross sections showed that this was not possible. The peak soil accelerations, for example, can be orders of magnitude greater than either pendulum acceleration. Two

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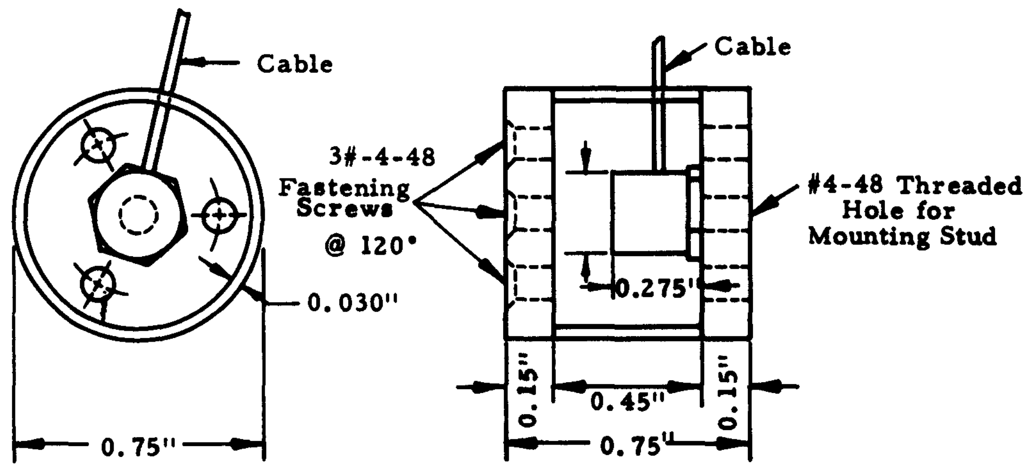
* Columbia Research Laboratories 607-1.

** Kistler Instrument Corporation, N. Tonawanda, New York, Model 566.



Open Top View

Side View with Cap

Fig. 11 INITIAL ACCELEROMETER DESIGN

other methods were used instead: 1) observation of the effect of certain changes such as mounting of accelerometer within case and orientation of gage in soil, and 2) comparison of integrated velocity records.

A series of experiments conducted with this original gage design resulted in the following conclusions:

1. When mounted on a pendulum, the response of this gage and the pendulum accelerometer were identical.
2. When embedded in soil, both the cable forces and soil pressure on the case produced signals which were at least as great as those produced by acceleration.

The cable effects were eliminated by looping the cable inside the case and clamping it down with a screw. It was necessary to mount the accelerometer off-center in the base to do this, but this arrangement does not appear to be objectionable. To illustrate the pressure effects in one test, the gage was placed in the soil but in contact with the reaction pendulum.

The peak acceleration indicated by the soil gage was approximately ten times that of the pendulum, i.e., the pressure effect was ten times the acceleration effect. The magnitude of pressure effects were suprising because the accelerometer transducer was mounted properly with a stud inside the case avoiding contact with the rest of the case. Apparently this subminiature accelerometer is especially susceptable to extraneous effects.

A new case was designed (Figure 12) again with a ratio of height to diameter of one, but slightly larger in size (0.85 in. diameter). The most important changes are the thicker more rigid base and a blind stud hole for mounting the accelerometer. The accelerometer is mounted off-center and cable clamped, as previously described, to minimize cable effects. This design proved insensitive to point pressure, uniform pressure, and lateral pressure. Average densities were 114 pcf, and 177 pcf, respectively giving density ratios of approximately 1.08 and 1.68.

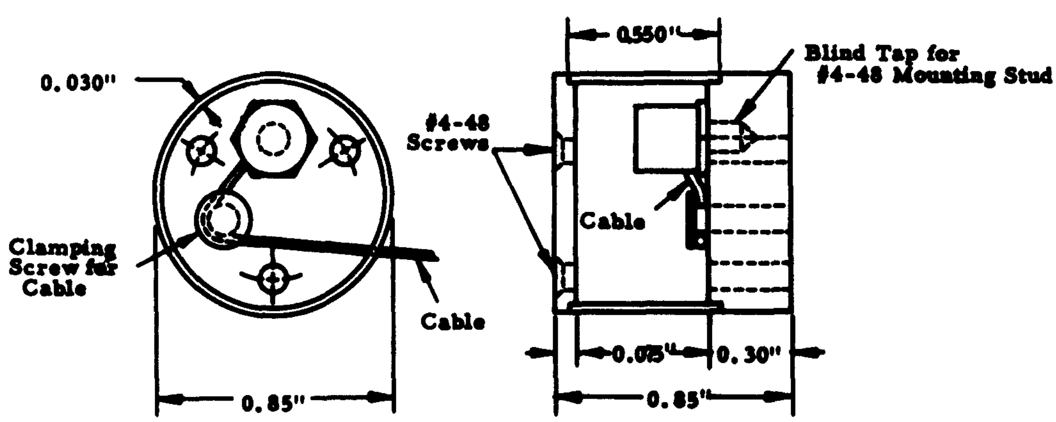


Fig. 12 REVISED ACCELEROMETER DESIGN

No other difficulties were encountered with this gage until the shock tube experiments were initiated. Moisture effects on the gage were seriously hampering the investigation. It was determined that the moisture in the clay entering through the case, connectors and cable insulation shorted the piezoelectric element causing severe drift of the charge amplifier and malfunctioning of the transducer. Upon discovery of the source of difficulty the cable was coated with a liquid latex compound. This eliminated the moisture problem if the gage was not permitted to stay in the clay for more than about 12 hr.

A third effect on the gage was temperature. Any rapid temperature change caused excessive zero shift in the trace, so it was required to wait until the temperatures stabilized in the soil before testing. This effect, however, was not serious since it occurred only when handling the gage, and by the time the experiment was to be performed, it had stabilized.

4. RESULTS OF LABORATORY STUDY

A. Pendulum Experiments

After the effects of pressure had been eliminated by the design of the new encasement, a series of experiments using the pendulum apparatus was performed. These experiments were designed in part to determine the effect of density mismatch between gage and the surrounding medium. To magnify any effects, sand specimens of low relative density were used at confining pressures of 5 and 12.5 psi. Values of sand densities for various tests range from 99.1 to 101.4 pcf which represents about 22 percent relative density.

Since the sand density was held approximately constant the density mismatch was created by using the aluminum and steel encased accelerometers. In addition, a series of experiments using a different geometry was performed. This was accomplished by attaching a disk to the gage encasement (Figure 13). The pendulum tests also provided information on the reproducibility of results under carefully controlled conditions.

After the pressure and cable effects had been eliminated four tests (Series A) were performed to investigate reproducibility. The first three specimens were subjected to essentially identical impact sequences; the fourth involved many more impacts at each confining pressure. The aluminum accelerometer was used.

Typical pendulum and embedded accelerometer records are shown in Figure 14 and 15. Basically the embedded gage record consists of three characteristic features; a sharply peaked short duration acceleration, followed by a longer duration deceleration and a final damped oscillation which represents the vibration of the specimen at the completion of impact. At the lower confining pressures the peak impact pendulum deceleration is substantially reduced because of the lower specimen stiffness. This results in reduced intensity of impact so that the positive and negative portions of the embedded accelerometer record are lower in magnitude and longer in duration than at the higher confining pressures.

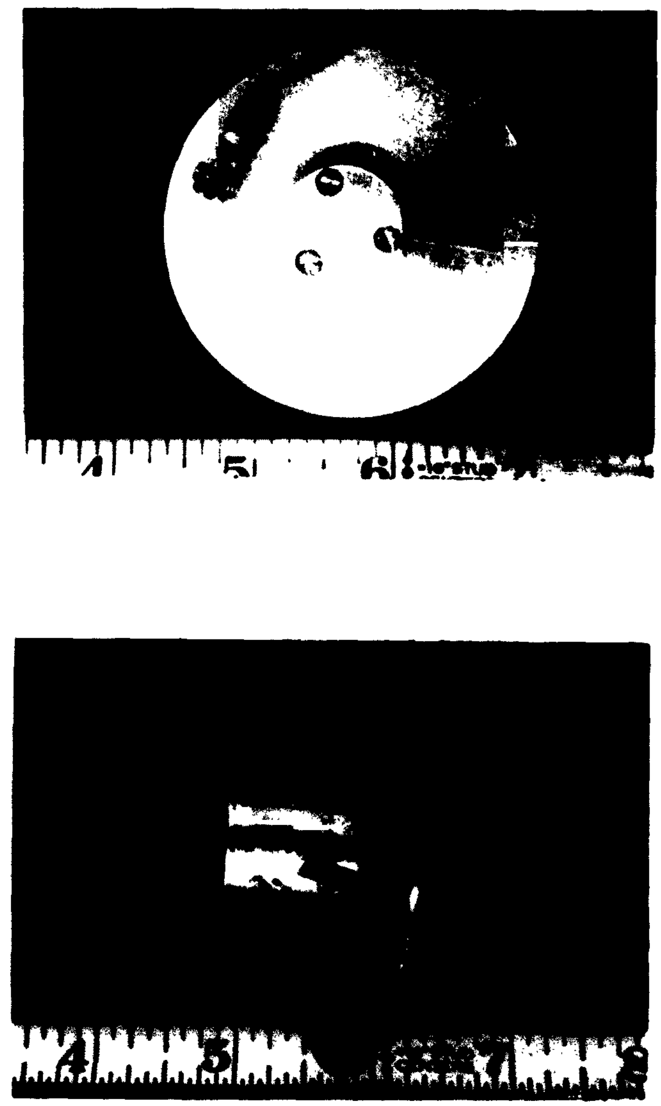
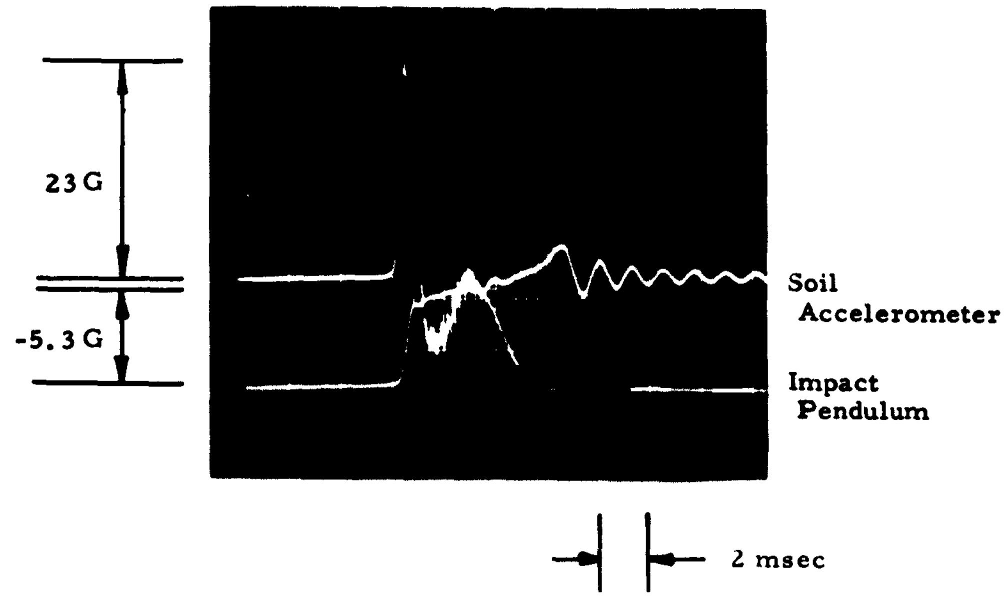


Fig. 13 ACCELEROMETER CASE WITH DISK ATTACHED



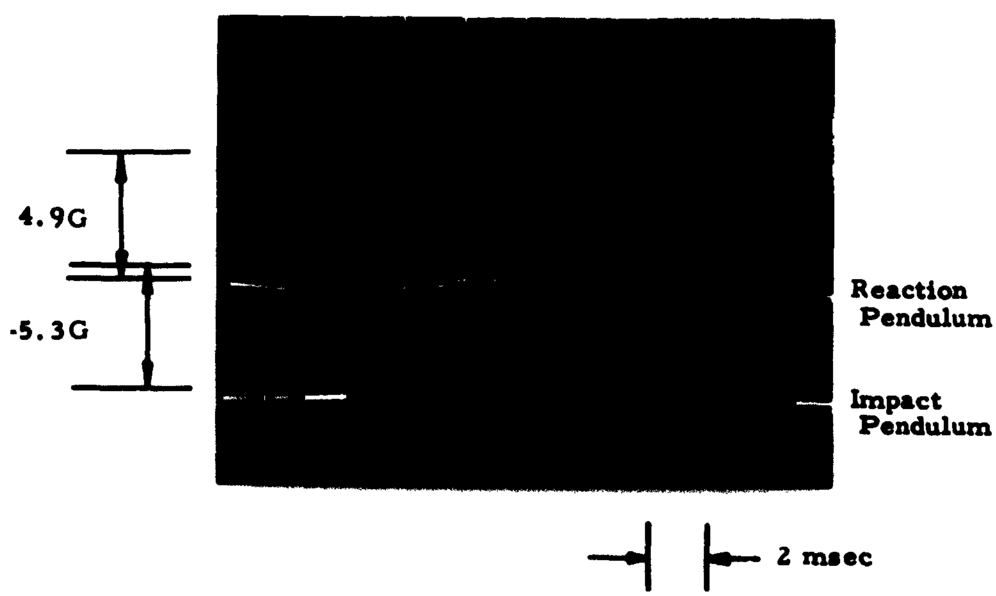


Fig. 14 TYPICAL PENDULUM ACCELEROMETER RECORDS, I
(Confining Pressure = 12.5 psi, Impact Velocity = 0.76 fps, Aluminum Accelerometer)

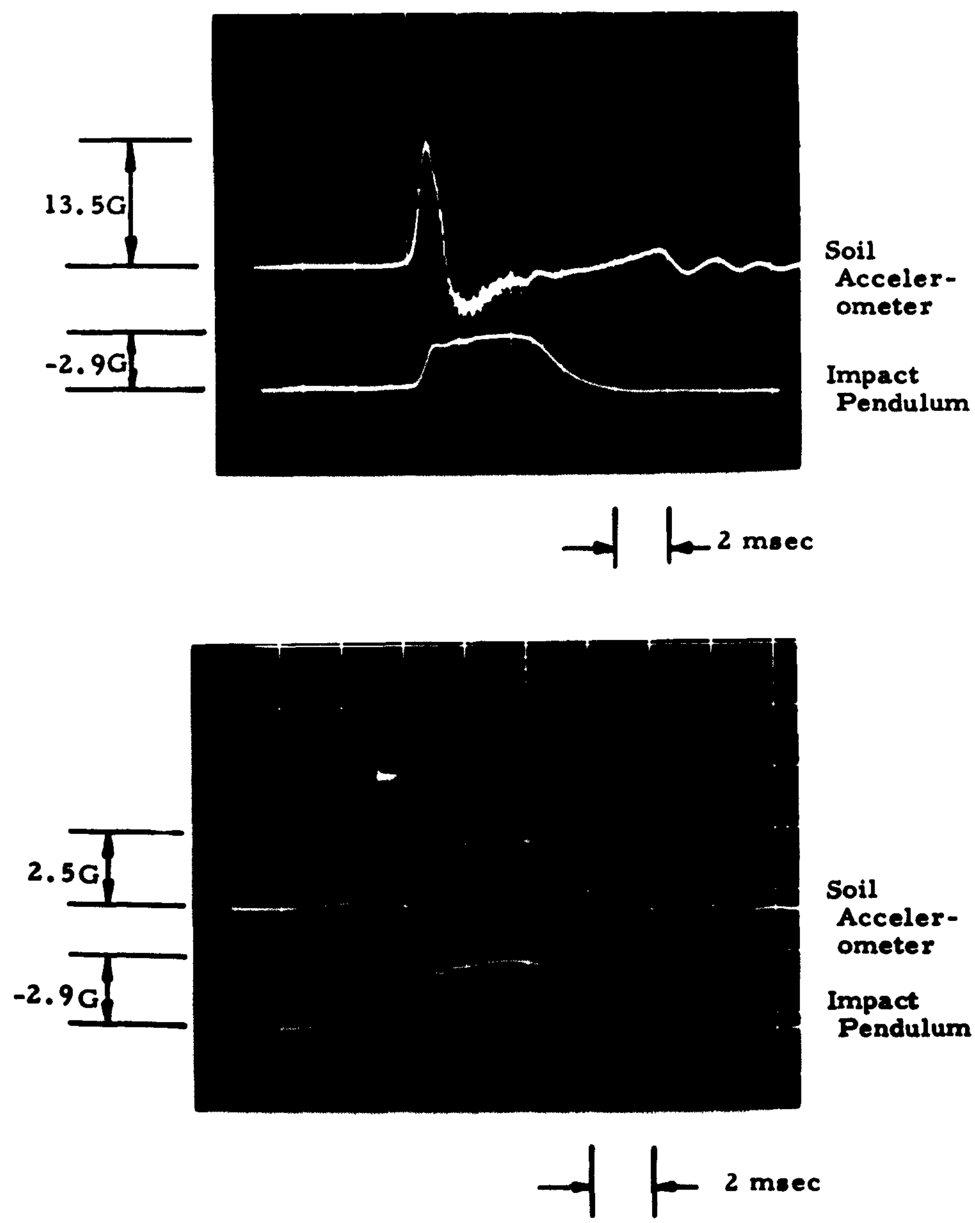


Fig. 15 <u>TYPICAL PENDULUM ACCELERATION RECORDS, II</u>
(Confining Pressure = 5 psi, Impact Velocity = 0.76 fps, Aluminum Accelerometer)

The acceleration results for Series A are shown in Figure 16 and listed in Table 3. The peak positive acceleration is plotted as a ratio of the maximum impact deceleration. Either the maximum impact deceleration or maximum reaction acceleration could have been used since they are both about equal. For each of the four specimens, the data are divided into groups representing the various confining pressures and impact velocities. The acceleration ratio was used rather than soil acceleration alone in an attempt to compensate in part for minor variations in density and impact sequence from specimen to specimen.

In Figure 16 the range and average of the values for each combination of velocity and confining pressure are shown for the first three tests. The fourth test is not included because there was a substantial change in impact sequence which appeared to have influenced the results. This range of values for each group may be taken as an approximate indication of reproducibility of the test. The maximum deviation of values from the average for each group ranges from 4 to 58 percent. The largest variation occurs for the 12.5-psi, 0.76-fps group which represents the first few impacts. There was a substantial increase in peak soil acceleration between the first and second impacts (the first impact is not shown for all tests). This may be due to alignment of specimen, or placement technique, or the fact that the specimen changes most between the first and second impacts. Without the first group the maximum deviation is 20 percent. The average deviation is 15 percent including the first group and 10 percent without this group.

The presentation of data in terms of acceleration ratio obviously does not correct for the effects of impact velocity and confining pressure. As the impact velocity increases the ratio increases, hence the soil acceleration increases with respect to the impact end deceleration. This might be expected because the higher the impact velocity the faster the soil must accelerate from rest up to speed, all other factors equal. The higher ratios at the lower confining pressures for the same impact velocity might be unexpected since the specimen is less stiff. However, as Table 3 shows, both the soil acceleration and impact deceleration decrease at the lower confining pressure. The

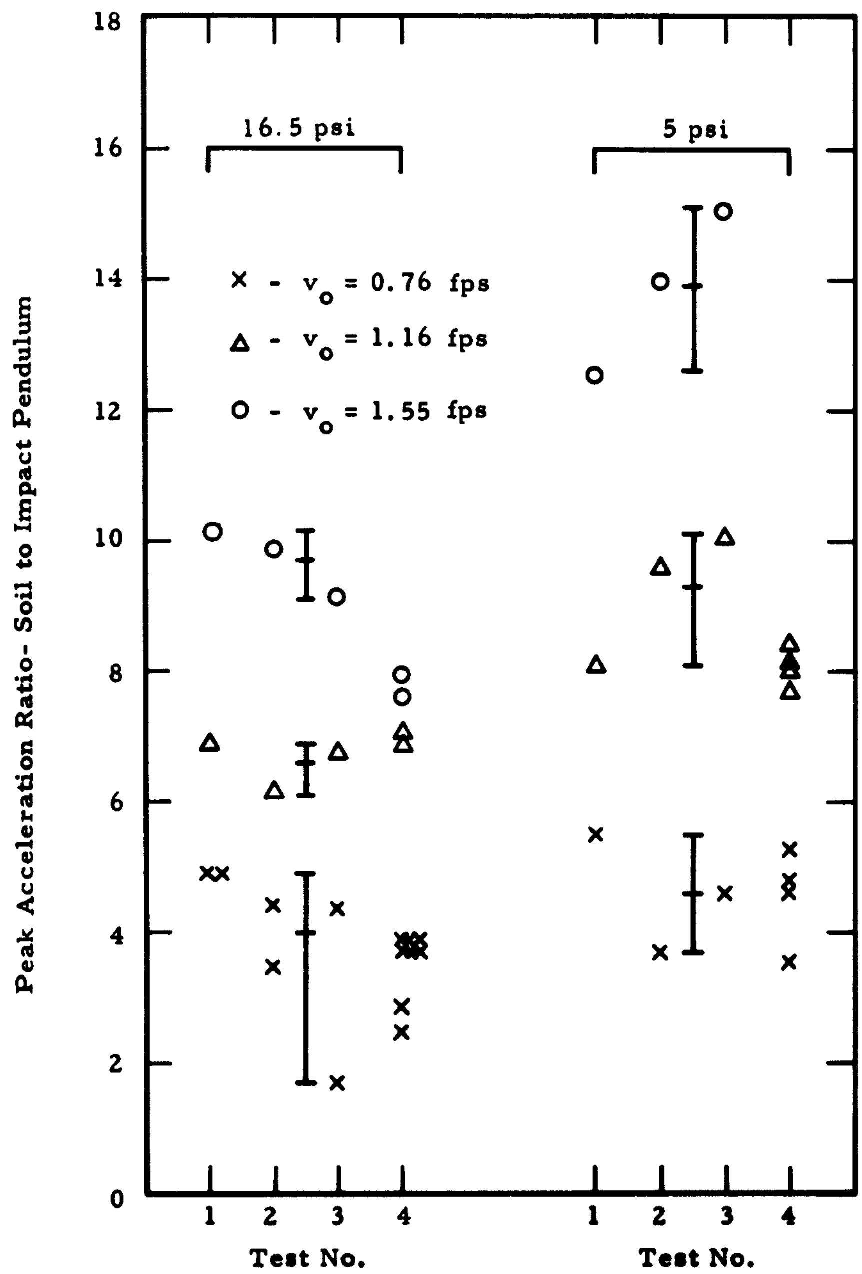


Fig. 16 ACCELERATION RESULTS FOR PENDULUM SERIES A

TABLE 3

RESULTS OF PENDULUM TESTS, SERIES A

Series and Impact		Accelerometer Condition	Initial Density, γ_o, (pcf)	Confining Pressure, σ_3, (psi)	Impact Velocity v_o, (fps)	Peak Soil Acceleration, (G)		Peak Pendulum Acceleration, (G)		Ratio of Soil Acceleration to Impact End Acceleration	
						Positive	Negative	Reaction	Impact	Positive	Negative
A-1	1	Al Case (New Design)	100.5	12.5	0.775	--	6.91	4.06	4.46	--	1.55
	2				0.775	23.0	6.35	4.67	4.80	4.90	1.32
	3				0.775	25.9	6.35	4.81	5.25	4.94	1.21
	4				1.162	42.6	6.91	5.65	6.20	6.88	1.12
	5				1.550	69.1	8.07	6.60	6.81	10.15	1.18
	6			5	0.775	16.1	4.31	2.80	2.94	5.48	1.47
	7				1.162	27.6	4.03	3.03	3.38	8.10	1.19
	8				1.550	46.1	5.76	3.50	3.67	12.55	1.57
A-2	1	Al Case (New Design)	101.4	12.5	0.775	17.3	5.30	4.67	5.01	3.45	1.06
	2				0.775	23.6	5.48	4.91	5.36	4.40	1.02
	3				1.162	30.2	6.91	5.75	6.36	6.16	1.08
	4				1.550	71.5	9.23	6.60	7.22	9.90	1.28
	5			5	0.775	11.0	4.04	2.80	2.99	3.68	1.35
	6				1.162	34.6	5.76	3.46	3.61	9.60	1.60
	7				1.550	76.0	5.76	3.65	3.78	20.10	1.52
	8				1.550	57.6	6.91	3.84	4.11	14.00	1.68
A-3	1	Al Case	99.1	12.5	0.775	8.06	4.61	4.30	4.68	1.73	0.99
	2				0.775	23.05	6.91	4.86	5.30	4.36	1.31
	3				1.162	41.5	6.91	5.65	6.14	6.76	1.13
	4				1.550	62.5	8.06	6.07	6.86	9.12	1.17
	5			5	0.775	13.25	4.61	2.52	2.87	4.61	1.61
	6				1.162	36.9	5.76	3.32	3.66	10.05	1.58
	7				1.550	58.8	6.91	3.36	3.89	15.10	1.78
A-4	1	Al Case	100.9	12.5	0.775	17.55	4.95	5.61	6.15	2.86	0.81
	2				0.775	14.90	4.72	5.65	6.10	2.45	0.78
	3				0.775	26.2	7.20	6.03	6.49	3.90	1.11
	4				0.775	25.9	6.90	6.16	6.76	3.84	1.02
	5				0.775	26.4	8.06	6.31	6.76	3.91	1.19
	6				0.775	26.5	8.92	6.31	6.88	3.86	1.30
	7				0.775	26.8	8.64	6.40	6.95	3.86	1.24
	8				0.775	27.6	9.20	6.54	7.05	3.91	1.30
	9				1.162	53.0	10.35	7.00	7.50	7.07	1.38
	10				1.162	53.0	13.80	7.89	7.73	6.86	1.79
	11				1.550	66.2	17.25	8.41	8.75	7.56	1.92
	12				1.550	69.6	14.40	8.41	8.75	7.96	1.65
	13			5	0.775	14.4	5.46	3.04	4.11	3.50	1.33
	14				0.775	20.4	7.20	3.27	4.45	4.60	1.66
	15				0.775	21.6	6.90	3.04	4.12	5.25	1.67
	16				0.775	21.6	7.48	3.32	4.51	4.78	1.66
	17				1.162	36.8	8.06	3.36	4.80	7.68	1.68
	18				1.162	40.3	6.34	3.36	4.80	8.40	1.32
	19				1.162	35.1	7.48	3.50	4.40	8.00	1.70
	20				1.162	35.7	7.48	3.55	4.40	8.12	1.70

latter decreases more thus increasing the ratio. These effects on the ratio are merely a consequence of data presentation and have no effect on conclusions since the various groups are not being compared.

Velocity records were obtained by integration for one set of acceleration records from Series A (Figure 17). The purpose was to provide a check on the validity of the soil acceleration measurements. The final velocity of the soil accelerometer (A-3) is about the same as that of the impact pendulum. It should be closer to that of the reaction end to which it is attached since equilibrium conditions have been reached and the impact pendulum is no longer in contact with the specimen. No suitable explanation could be found for this discrepancy. Possible errors such as those due to gage sensitivity or base line shift were examined but these did not appear large enough to correct the problem. Placement conditions or density mismatch should not cause this effect because even though they might distort the gage response, nevertheless, when equilibrium is reached the specimen must have the same velocity as the reaction pendulum.

A second series of tests (Series B) was conducted to determine the effect of density mismatch on accelerometer response. Typical acceleration records are shown in Figure 18. The records are of the same general shape as for Series A. However, the proportion of negative to positive area was noticeably less in Series B thus suggesting that velocity correlation might be better. The high frequency noise was also reduced, possibly because of a change in mounting of the accelerometer transducer within the case. There was no discernable difference in the shapes between the steel and aluminum accelerometer records for Series B.

The results of Series B are presented in Figure 19 in terms of both positive and negative peak acceleration ratios and listed in Table 4. The negative ratios, i.e., ratio of first negative peak of soil gage acceleration to peak impact pendulum deceleration, are small and difficult to measure accurately so they were not examined in detail. There is a more or less random variation of these values with overlap from group to group. The positive ratios fall into groups with respect to confining pressure and impact velocity as before.

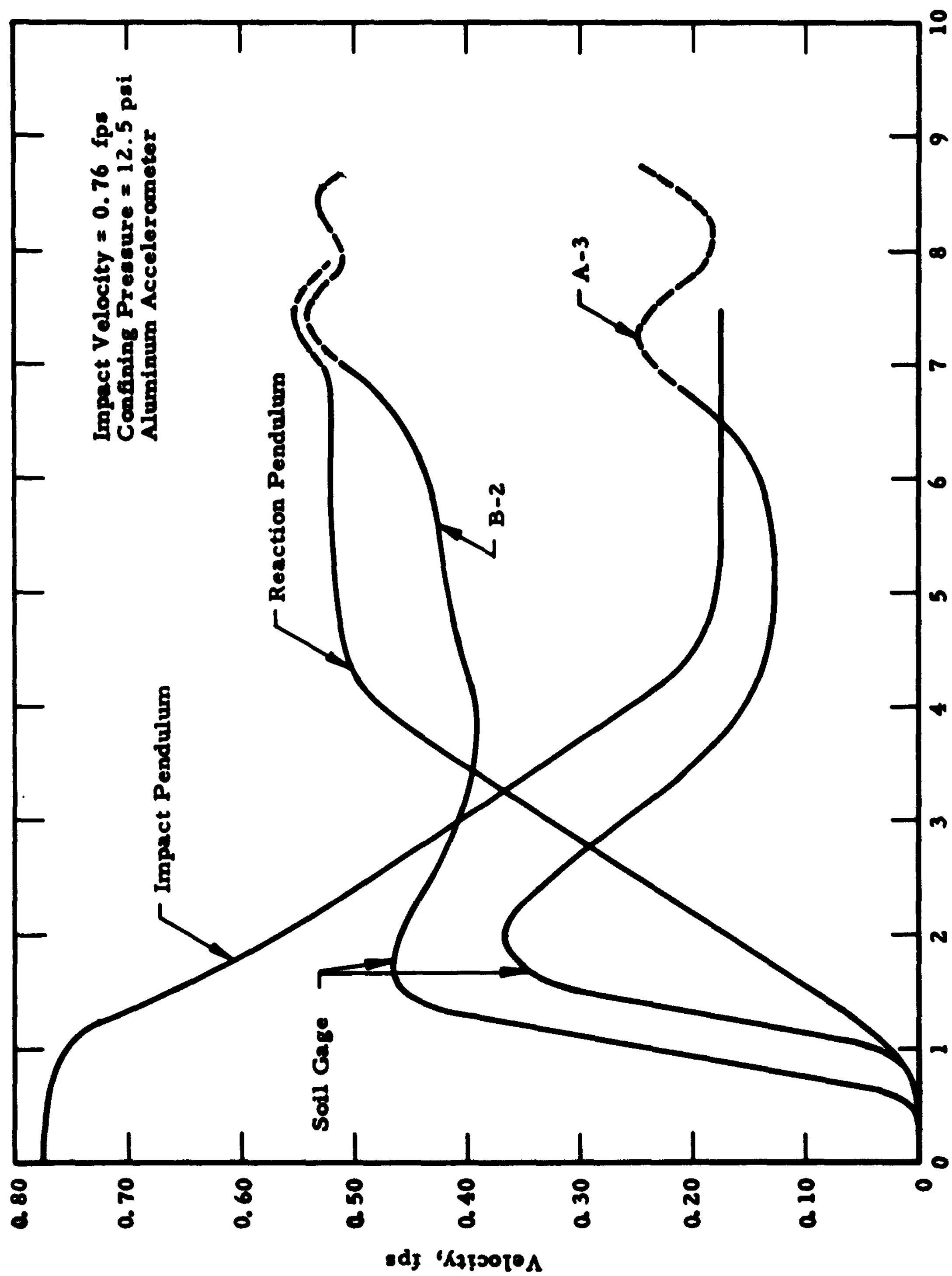


Fig. 17 **VELOCITY RECORDS OBTAINED BY INTEGRATION**

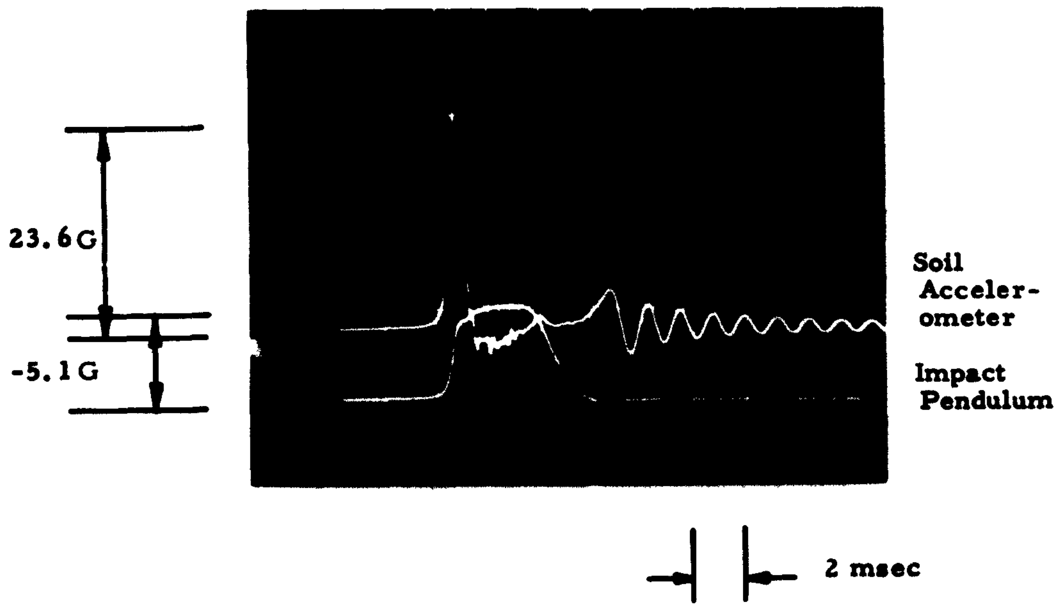


Fig. 18 <u>ACCELEROMETER RESPONSE IN SERIES B</u>
(Confining Pressure = 12.5 psi, Impact Velocity = 0.76 fps, Aluminum Accelerometer)

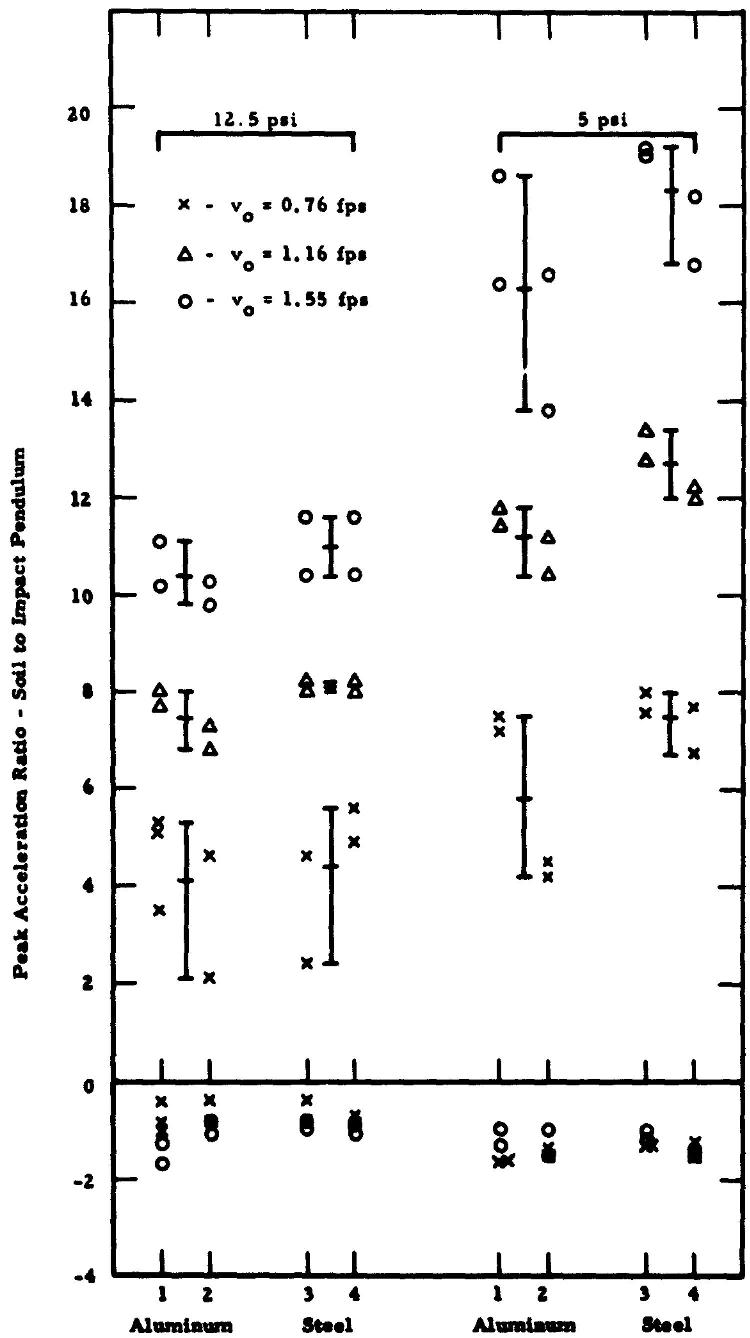


Fig. 19 ACCELERATION RESULTS FOR PENDULUM SERIES B

TABLE 4

RESULTS OF PENDULUM TESTS, SERIES B

Series and Impact	Accelerometer Condition	Initial Density γ_o, (pcf)	Confining Pressure, σ_3, (psi)	Impact Velocity v_o, (fps)	Peak Soil Acceleration, (G)		Peak Pendulum Acceleration, (G)		Ratio of Soil Acceleration to Impact End Acceleration	
					Positive	Negative	Reaction	Impact	Positive	Negative
B-1 1	Al Case	99.6	12.5	0.775	16.7	2.02	4.2	4.74	3.53	0.43
2				0.775	27.6	4.61	--	5.46	5.05	0.85
3				0.775	30.5	6.05	5.45	5 75	5.30	1.05
4				1.162	53.5	6.91	--	6.65	8.05	1.05
5				1.162	54.1	9.80	6.75	7.16	7.66	1.37
6				1.550	86.3	9.80	7.45	7.79	11.10	1.26
7			12.5	1.550	86.3	14.4	8.00	8.45	10.20	1.71
8			5	0.775	27.4	5.76	3.50	3.66	7.50	1.57
9				0.775	26.2	5.76	3.45	3.66	7.18	1.57
10				1.162	48.5	5.76	3.82	3.95	11.40	1.02
11				1.162	45.0	4.03	3.97	4.11	11.80	1.40
12				1.550	79.5	4.04	4.01	4.28	18.60	0.95
13				1.550	69.0	5.76	4.20	4.45	16.40	1.29
B-2 1	Al Case	99.6	12.5	0.775	9.21	3.45	4.06	4.35	2.12	0.80
2				0.775	23.6	2.02	4.76	5.13	4.60	0.39
3				1.162	45.0	4.61	5.73	6.15	7.33	0.75
4				1.162	46.1	6.91	6.45	6.76	6.82	1.02
5				1.550	7.65	5.76	7.00	7.40	10.32	0.78
6				1.550	77.6	8.65	7.60	7.95	9.76	1.09
7			5	0.775	13.8	5.2	2.98	3.32	4.16	1.56
8				0.775	15.3	4.6	3.22	3.38	4.52	1.36
9				1.162	41.5	3.46	3.50	3.72	11.15	0.93
10				1.162	40.3	4.9	3.64	3.89	10.35	1.26
11				1.550	66.2	4.04	3.96	4.00	16.55	1.01
12				1.550	57.6	6.34	3.96	4.17	13.80	1.52
B-3 1	Steel Case	100.0	12.5	0.775	10.1	3.45	3.97	4.18	2.42	0.83
2				0.775	23.0	1.73	4.58	4.96	4.64	0.35
3				1.162	47.3	4.04	5.60	5.92	8.00	0.68
4				1.162	53.0	5.76	6.11	6.49	8.19	0.89
5				1.550	83.5	5.76	7.00	7.21	11.55	0.80
6				1.550	80.6	7.50	7.44	7.78	10.35	0.97
7			5	0.775	27.1	4.32	3.32	3.38	8.00	1.28
8				0.775	25.9	4.32	3.27	3.44	7.55	1.25
9				1.162	44.0	2.88	3.50	3.66	13.35	0.79
10				1.162	4.66	4.60	3.50	3.66	12.75	1.25
11				1.550	80.0	4.04	3.97	4.17	19.15	0.97
12				1.550	81.3	5.19	4.16	4.28	19.00	1.21
B-4 1	Steel Case	100.1	12.5	0.775	23.6	3.46	4.58	4.85	4.86	0.71
2				0.775	29.4	4.15	5.00	5.25	5.60	0.79
3				1.162	50.6	5.76	5.84	6.20	8.17	0.93
4				1.162	54.1	6.91	6.16	6.76	8.02	1.02
5				1.550	86.5	6.91	7.01	7.44	11.62	0.93
6				1.550	81.9	8.64	7.40	7.90	10.40	1.09
7			5	0.775	26.5	4.61	3.27	3.44	7.70	1.34
8				0.775	23.6	5.18	3.27	3.50	6.75	1.48
9				1.162	43.8	2.88	3.50	3.66	11.95	0.79
10				1.162	46.1	5.18	3.60	3.78	12.20	1.37
11				1.550	73.8	5.76	3.83	4.05	18.20	1.42
12				1.550	72.0	6.34	4.16	4.28	16.80	1.48

Test reproducibility was again evaluated by computing the deviation of values within each group for each accelerometer. For the aluminum accelerometer the deviation values range from 5 to 50 percent and average 17 percent. For the steel accelerometer the values range from 1 to 45 percent and average 10 percent. The difference between these two sets of results is probably not a function of accelerometer type. As for Series A, the greatest deviation has associated with the first few impacts, i.e., there is always a significant difference between the first and second impacts for any specimen. In all other cases successive impacts within any one group produce similar results, i.e., reproduce reasonably well.

As another measure of reproducibility, individual ratios representing essentially identical conditions (confining pressure, impact velocity and impact number) were compared for two specimens with the same type accelerometer. This will improve reproducibility figures because there is always some change in the ratio for successive impacts on one specimen even with all other conditions held constant. On this basis the deviation for the aluminum accelerometer ranges from 1 to 28 percent, averaging 10 percent; the deviation for the steel accelerometer ranges from 1 to 34 percent and averages 6 percent.

The variation in the average group ratio between the steel and aluminum accelerometer may be taken as an indication of the effect of density mismatch. Figure 19 shows a consistently larger ratio for the steel accelerometer compared to the aluminum accelerometer. The percent increase in average group values ranges from 5 to 25 percent and averages 12 percent. Thus, for an increase in gage density of 55 percent it appears that there was about a 12 percent increase in gage response for the same input.

Although it is possible that the change in accelerometers may have changed the specimen response or even the input conditions, the difference may also be explained in terms of gage density. The embedded accelerometer may be considered as a simple single-degree-of-freedom mass-spring system as illustrated in Figure 20. Because of the high natural frequency of the piezoelectric sensor and the rigidity of the case, it has been assumed that the relative motion between the sensor and the case can be ignored. The stiffness k and damping c occur within the soil specimen and are in part a result of the gage interaction with the soil.

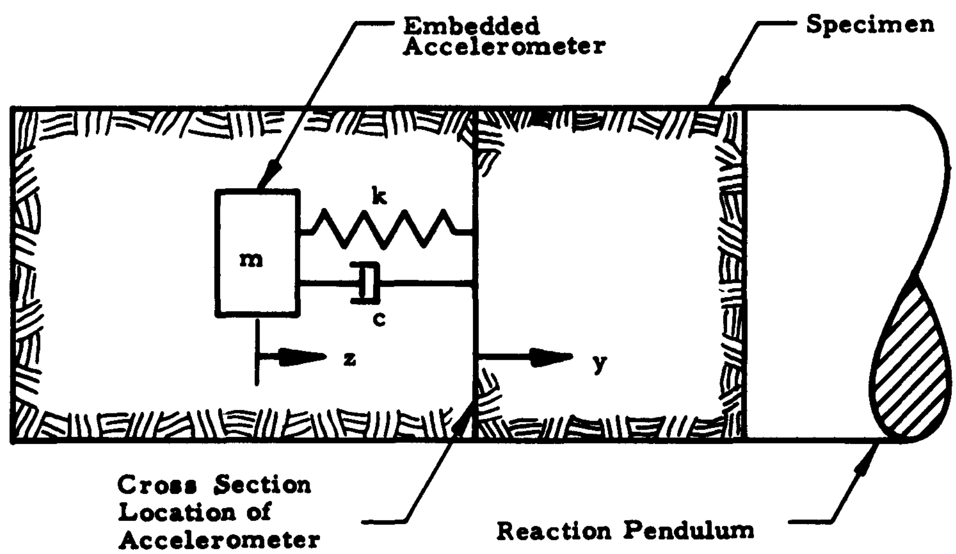


Fig. 20 IDEALIZED SOIL-ACCELEROMETER SYSTEM

The accelerometer mass is m, the motion of the accelerometer case is $z(t)$, and the equivalent motion of the cross section is $y(t)$. Let the initial acceleration time history of the cross section be represented by a half-sine-wave pulse. The motion of the accelerometer will follow that of the cross section with an accuracy which depends upon the natural frequency of the system ($\sqrt{k/m}$) and the damping c.

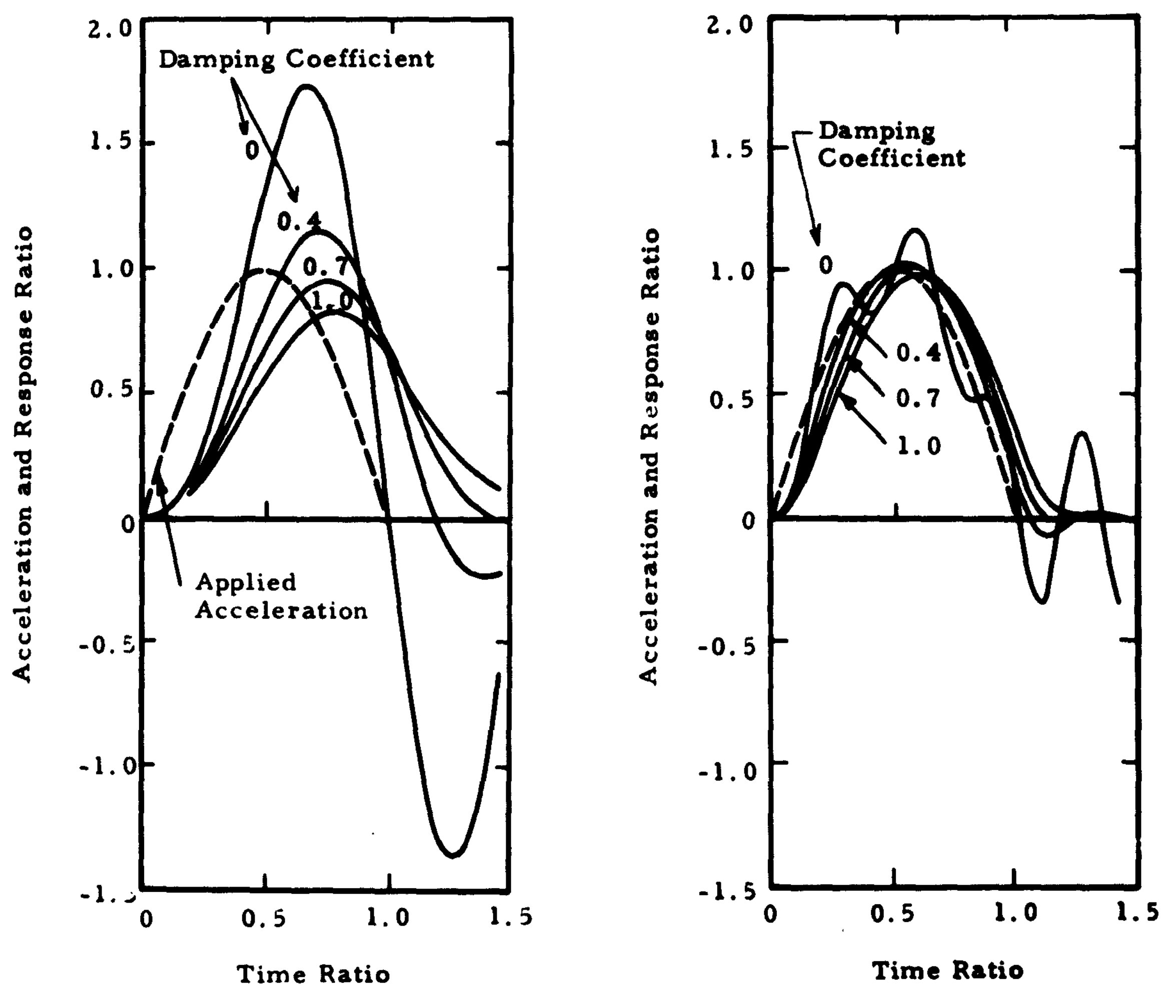
The theoretical accelerometer response for this idealized system is shown in Figure 21 for several values of frequency and damping.[23] If the values of k and c are assumed to be the same for both the aluminum and steel accelerometers then the ratio of the natural frequency of the aluminum system to the steel system would be equal to

$$\sqrt{\frac{\gamma_{\text{steel}}}{\gamma_{\text{aluminum}}}}$$

where the γ represents the accelerometer densities. For this study the ratio of natural frequencies is 1.24, i.e., the natural frequency of the aluminum accelerometer is about 25 percent greater than that of the steel. Figure 21 shows that for low damping coefficients the lower natural frequency results in a greater peak recorded acceleration than the higher natural frequency. The observed results in Figure 19 can thus be explained in terms of a low-damped mass-spring system. Of course this explanation is no proof because at higher damping the reverse is true. However, free vibrations of the specimen at the end of impact (Figure 18) suggest a low degree of damping.

An analysis of the rise time of the embedded gage records was made in an attempt to further verify the effect of gage density. No significant differences were noticed with this method. However, this does not pose a contradiction because the accuracies of the rise time measurements were not sufficient to establish any correlation.

Integration of one of the embedded accelerometer records was performed for comparison with the velocity curves obtained in Series A (Figure 17). For the same impact and reaction pendulum response the gage in series B showed a more reasonable velocity curve. In particular, the final velocity of the reaction pendulum and that of the soil are in agreement.



(a) Accelerometer Period Equal to 1.014 times Duration of Pulse.

(b) Accelerometer Period Equal to 0.338 times Duration of Pulse.

Fig. 21 RESPONSE OF ACCELEROMETER TO HALF-SINE-WAVE PULSE [23]

Series C illustrates the effect of the disk on accelerometer response. For the first two specimens the aluminum accelerometer was used without the disk as in Series A and B. These two tests served also to confirm that pressure effects on the case were not significant. The polarity of the accelerometer was reversed between the two tests by reversing the case. The results in terms of acceleration ratio are given in Figure 22 and listed in Table 5. There is not a significant difference in the ratios between the two situations and the recorded traces were of the same shape. Therefore, it may be concluded that the pressure effects are absent.

A disk was then attached to the aluminum accelerometer and the gage placed in the soil so that the disk was located on the center cross section of the specimen. The position of the accelerometer case in the sand was thus the same as before. The accelerometer records were of the same shape with and without the disk.

Velocity records were obtained by integration for one of the tests with the disk (Figure 23). Although the final soil velocity is less than the final velocity of the reaction pendulum the agreement is close and the results are similar to that for Series B (Figure 17).

The results with the disk are given in Figure 22. For each set of impact velocity and confining pressure conditions the acceleration ratios are lower with the disk than without. The decrease ranges from 10 to 42 percent and averages 27 percent. It originally seemed that this decrease was a result of a change in coupling with the cross section and might have significant meaning. However, no satisfactory explanation for a decrease rather than an increase could be found. It appears more likely that the decrease is due to a change in cross section with which the gage is moving. Although the accelerometer case is in the same position in the specimen, without the disk the effective cross section is probably near the center of the case. With the disk the cross section is that at which the disk is located (Figure 7) which is approximately 4/10 in. further toward the reaction end of the specimen. It may be recalled that the peak acceleration at a cross section decreases by several orders of magnitude between the impact and reaction ends, a distance of only 4 in. It is reasonable then to expect a decrease of 27 percent in 4/10 in.

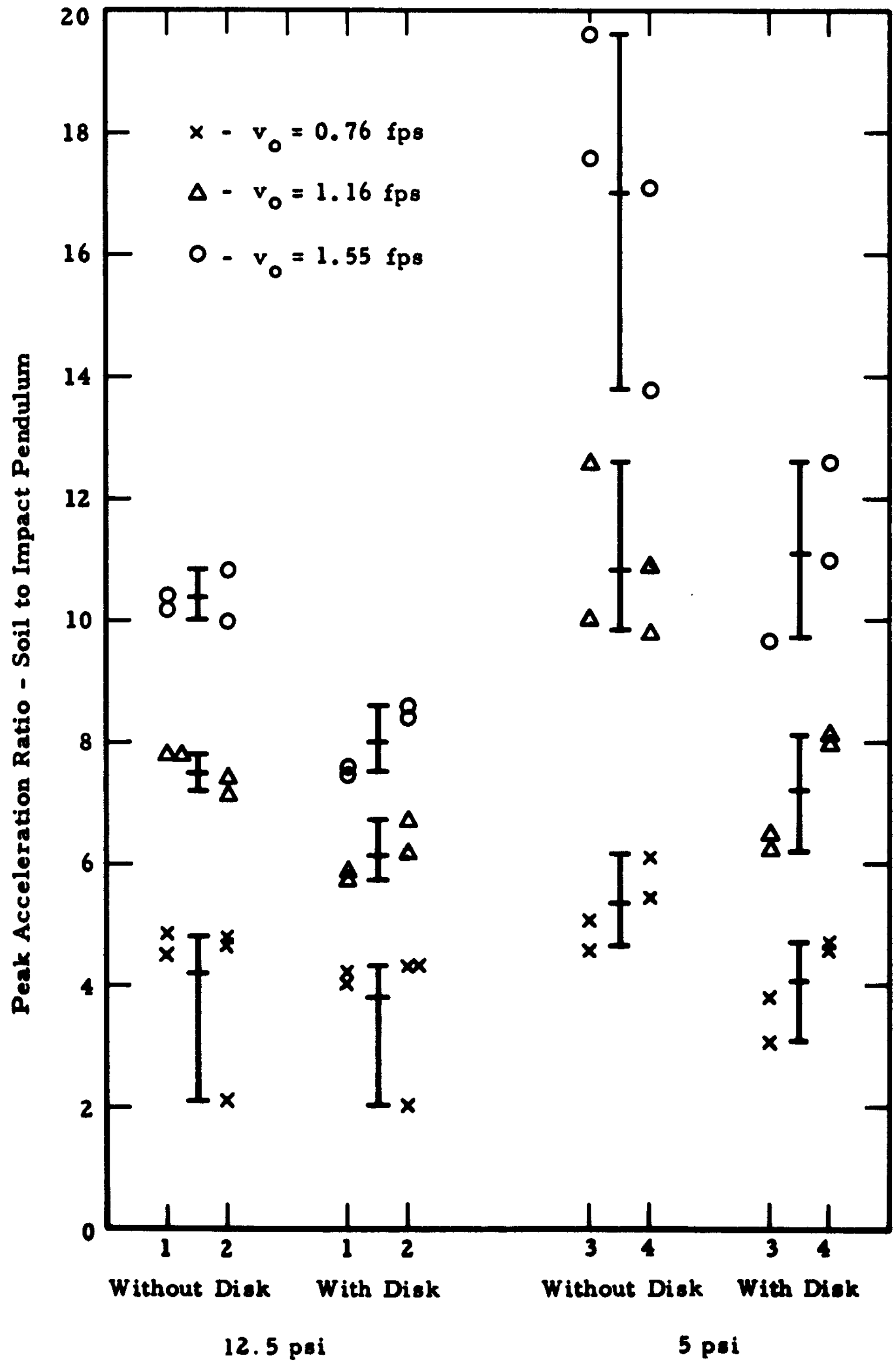


Fig. 22 ACCELERATION RESULTS FOR PENDULUM SERIES C

TABLE 5

RESULTS OF PENDULUM TESTS, SERIES C

Series and Impact		Accelerometer Condition	Initial Density γ_o, (pcf)	Confining Pressure, σ_3, (psi)	Impact Velocity, v_o, (fps)	Peak Soil Acceleration, (G)		Peak Pendulum Acceleration, (G)		Ratio of Soil Acceleration to Impact End Acceleration	
						Positive	Negative	Reaction	Impact	Positive	Negative
C-1	1	Case with Disk - Accelero-meter to-ward re-action end	100.6	12.5	0.775	24.2	2.02	4.9	5.41	4.47	0.37
	2				0.775	27.7	3.46	5.09	5.70	4.86	0.61
	3				1.162	53.0	4.6	6.02	6.76	7.84	0.68
	4				1.162	55.3	9.23	6.30	7.1	7.80	1.30
	5				1.550	80.8	5.76	7.24	7.90	10.20	0.73
	6				1.550	86.5	8.65	7.51	8.30	10.40	1.04
	7			5	0.775	15.6	4.04	3.03	3.38	4.61	1.19
	8				0.775	18.5	5.2	3.27	3.61	5.13	1.44
	9				1.162	49.7	4.04	--	3.95	12.56	1.02
	10				1.162	39.3	5.76	3.64	3.95	10.00	1.46
	11				1.550	80.8	5.76	3.78	4.12	19.60	1.40
	12				1.550	75.5	5.76	3.97	4.29	17.60	1.35
C-2	1	Case with Disk - Accelero-meter to-ward im-pact end	100.4	12.5	0.775	9.23	2.88	3.87	4.40	2.10	0.66
	2				0.775	24.5	1.73	4.57	5.06	4.84	0.34
	3				0.775	25.4	2.88	4.90	5.41	4.70	0.53
	4				1.162	45.0	5.76	5.84	6.30	7.15	0.92
	5				1.162	49.5	5.76	6.06	6.70	7.40	0.86
	6				1.550	80.7	5.76	6.63	7.44	10.85	0.78
	7				1.550	78.0	8.65	7.00	7.83	10.00	1.10
	8			5	0.775	21.9	4.03	3.27	3.55	6.17	1.13
	9				0.775	19.6	4.03	3.27	3.55	5.52	1.13
	10				1.162	42.6	2.30	3.80	3.89	10.95	0.59
	11				1.162	38.0	2.88	3.64	3.89	9.78	0.74
	12				1.550	70.5	3.45	3.68	4.11	17.10	0.84
	13				1.550	64.5	2.88	3.87	4.68	13.80	0.62
C-3	1	Al Case with Disk	100.9	12.5	0.775	28.0	--	6.30	6.88	4.07	--
	2				0.775	29.4	12.1	6.45	7.05	4.17	1.72
	3				1.162	50.6	9.2	7.93	8.56	5.91	1.07
	4				1.162	51.8	9.2	7.93	8.85	5.85	1.04
	5				1.550	74.4	10.9	9.10	9.86	7.55	1.11
	6				1.550	77.8	14.4	9.42	10.35	7.50	1.39
	7			5	0.775	12.1	3.8	3.64	3.94	3.07	0.96
	8				0.775	17.3	2.6	4.15	4.50	3.84	0.58
	9				1.162	32.3	3.5	4.67	5.00	6.46	0.70
	10				1.162	31.1	4.05	4.75	5.00	6.23	0.81
	11				1.550	54.6	5.8	5.14	5.64	9.70	1.03
	12				1.550	--	4.6	5.14	5.64	--	0.82
C-4	1	Same - Accelero-meter Glued with Epoxy	100.5	12.5	0.775	10.1	5.2	4.20	5.06	2.00	1.03
	2				0.775	25.4	2.3	4.90	5.91	4.30	0.39
	3				0.775	25.6	3.5	5.14	5.75	4.33	0.59
	4				1.162	47.8	3.5	6.50	7.08	6.76	0.50
	5				1.162	46.1	4.8	6.90	7.55	6.11	0.64
	6				1.550	75.5	5.2	7.92	8.74	8.65	0.60
	7				1.550	77.8	9.2	8.45	9.25	8.40	1.00
	8			5	0.775	18.5	2.9	3.68	4.05	4.57	0.72
	9				0.775	19.0	4.05	3.68	4.04	4.70	1.00
	10				1.162	35.7	2.9	4.20	4.46	8.01	0.65
	11				1.162	36.6	3.5	4.25	4.50	8.15	0.78
	12				1.550	64.0	5.8	4.67	5.06	12.61	1.14
	13				1.550	56.3	5.8	4.70	5.13	11.00	1.13

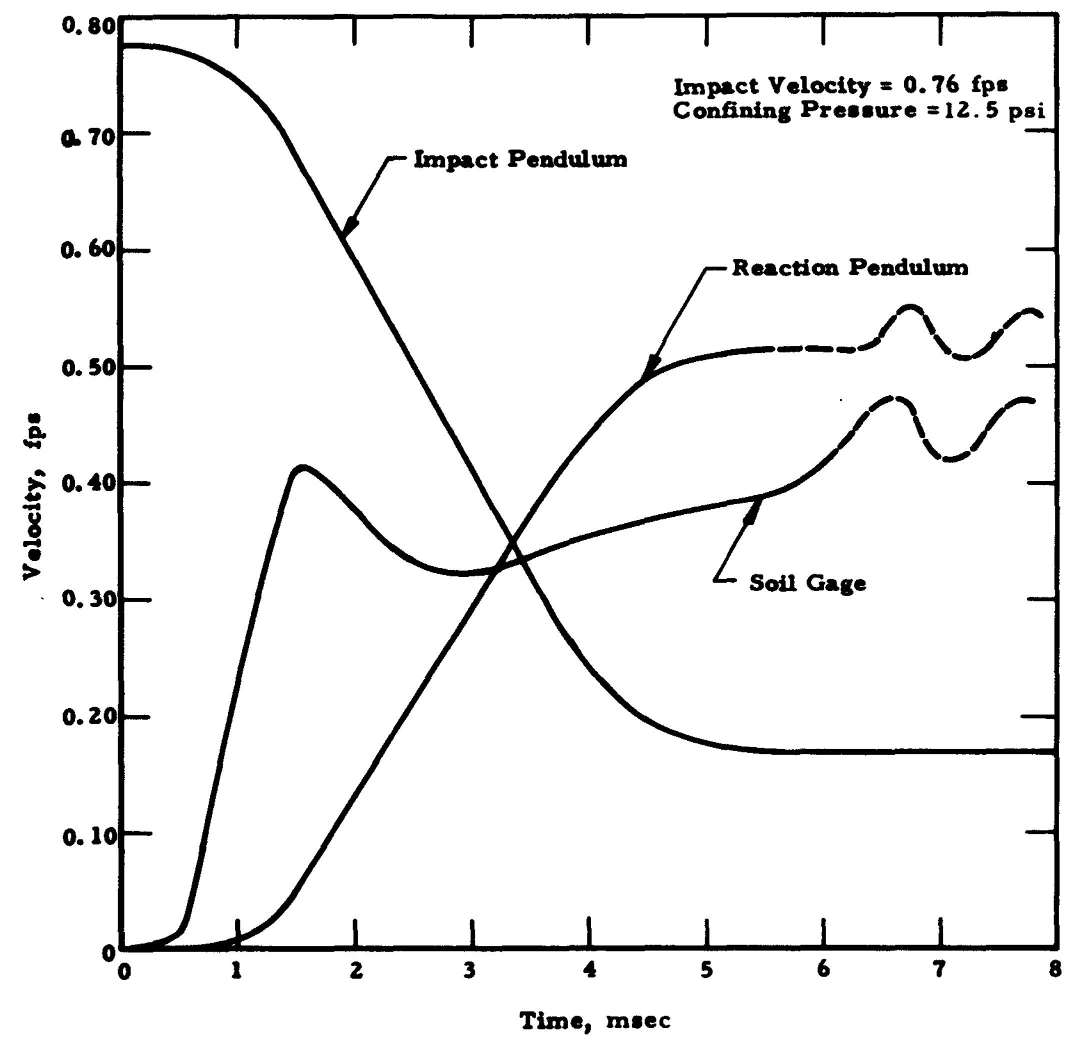


Fig. 23 VELOCITY RECORDS FOR ACCELEROMETER WITH DISK

The pendulum test results are summarized in Figure 24. The average and range of acceleration ratio for each group of data are shown and compared. The three series in which the aluminum accelerometer was used without the disk give about the same results. The results with the steel accelerometer are consistently higher than any of the tests with the aluminum accelerometer. This difference is believed to be due to the change in soil-gage density matching. However, the magnitude of this deviation is only about as great as the variation within the sets of data for the accelerometer alone. For comparison, a number of calibrations of the soil accelerometer were made to determine the reproducibility of the instrumentation. It was found that the calibration values varied $\pm$ 5 percent. Thus, as much as $\pm$ 5 percent variation in the results may be attributed to the instrumentation.

B. Shock Tube Experiments

These tests were performed to study the motion of a soil accelerometer under a laterally constrained soil condition. The gage placement methods and the type of clay used are discussed in detail in the procedures section. Both the aluminum and steel accelerometer were used giving two different ratios of gage-to-soil density. The compacted clay had a density of 115 pcf, thus, the ratios were 1.0 and 1.54. These gages were placed using heavy soil compaction, light soil compaction and grouting. The soil surface was loaded with an air shock pulse whose peak pressures were either 2, 4 or 6 psi. The length of the shock tube is sufficient that the reflected air shock does not reload the soil while the embedded gage measurements are being recorded.

Typical soil accelerometer records are shown in Figure 25. The distinguishing features are two or three major oscillations of roughly 700 to 900 cycles per second with higher frequency harmonics superimposed. These major oscillations apparently represent the free vibration of the clay specimen since a frequency of 800 cycles per second corresponds to a wave velocity of 3200 fps for the 2-ft-deep specimen. The soil acceleration is of course complicated by the presence of many reflections of the shock pulse from the rigid boundaries of the specimen.

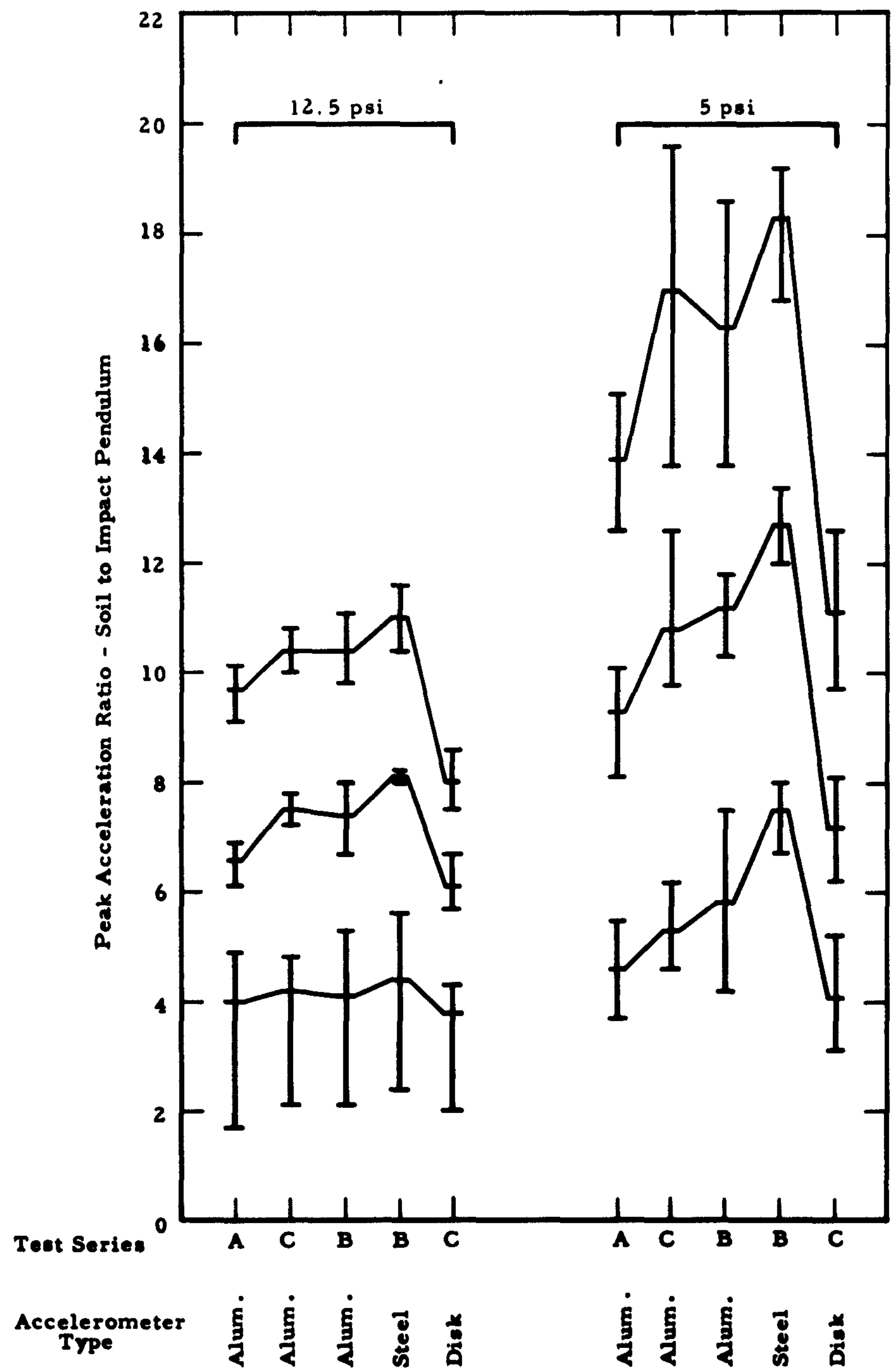
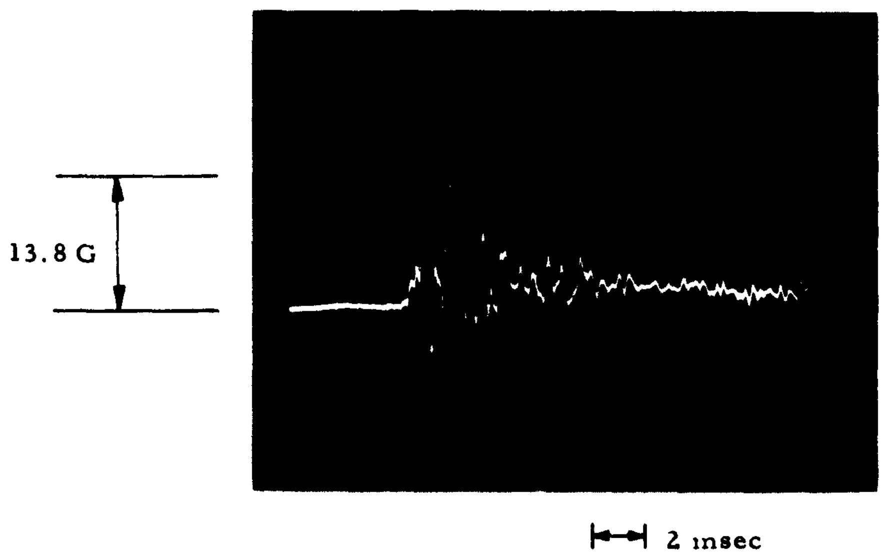
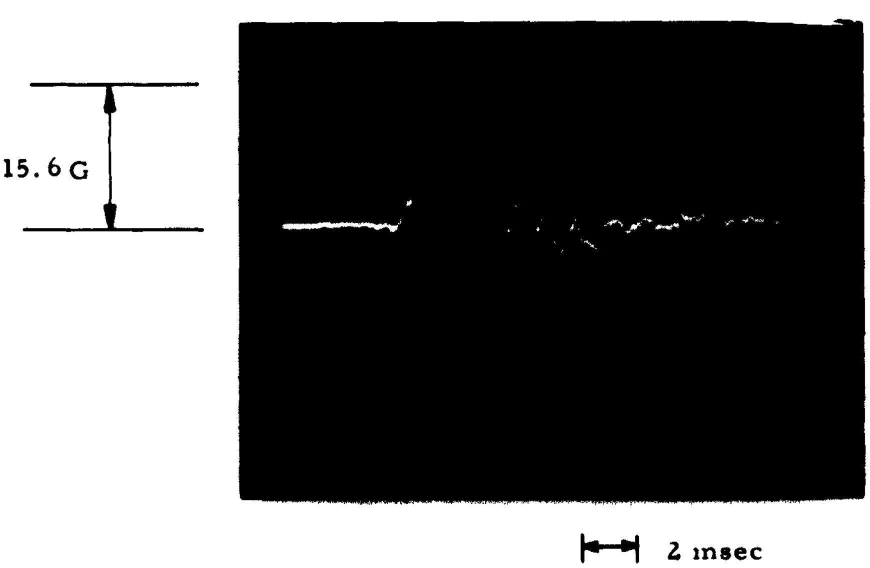


Fig. 24 **SUMMARY OF PENDULUM TESTS**



(a) Light Compaction



(b) Grout Placement

Fig. 25 TYPICAL SHOCK TUBE ACCELEROMETER RECORDS
(Steel Accelerometer, Shock Pressure = 4 psi)

The acceleration of the bottom of the soil container was measured for several shock pulses to ascertain whether motion of the container had a significant influence in the soil accelerations. The maximum container accelerations were about 10 percent of the maximum soil accelerations, hence, it was concluded that the embedded gage records could provide a meaningful measure of gage placement effects.

Two features of the gage records, the average rate of acceleration rise up to the first peak and the magnitude of several prominent peaks, were used for analysis. The peaks selected were the first positive one, the first negative one and the greatest negative one (usually the second major negative peak). The accuracy of the analysis is limited in part by the superimposed high-frequency oscillations. These oscillations may increase or decrease the peak values of the major oscillations depending upon the phase relationship between the two.

The peak values for the shock tube tests are summarized in Figures 26 through 29. To illustrate the results, the relationship between the three soil-acceleration peaks for the aluminum accelerometer embedded with the heavy soil compaction is shown in Figure 26. After one series of measurements, the gage was removed and embedded in the same manner. This provided measurements to obtain an indication of reproducibility of placement. The variation between the results for the two sets of data is no greater than the range of values for each series alone. With one or two exceptions this same degree of consistency is indicated by the other test series. The variation of the positive peaks for any one set of conditions, including reproducibility between two identical series, ranges from about $\pm$ 5 to $\pm$ 29 percent and averages $\pm$ 15 percent. The greatest variation occurred for the negative peaks reaching about $\pm$ 50 percent. For each test series there is a consistent increase in peak acceleration with increase in peak shock pressure, as would be expected.

Figures 27, 28 and 29 indicate the influence of gage density and placement conditions on peak acceleration. Both positive and negative peaks were consistently greater for the condition of light compaction compared to heavy compaction. This relationship held for both the aluminum and steel

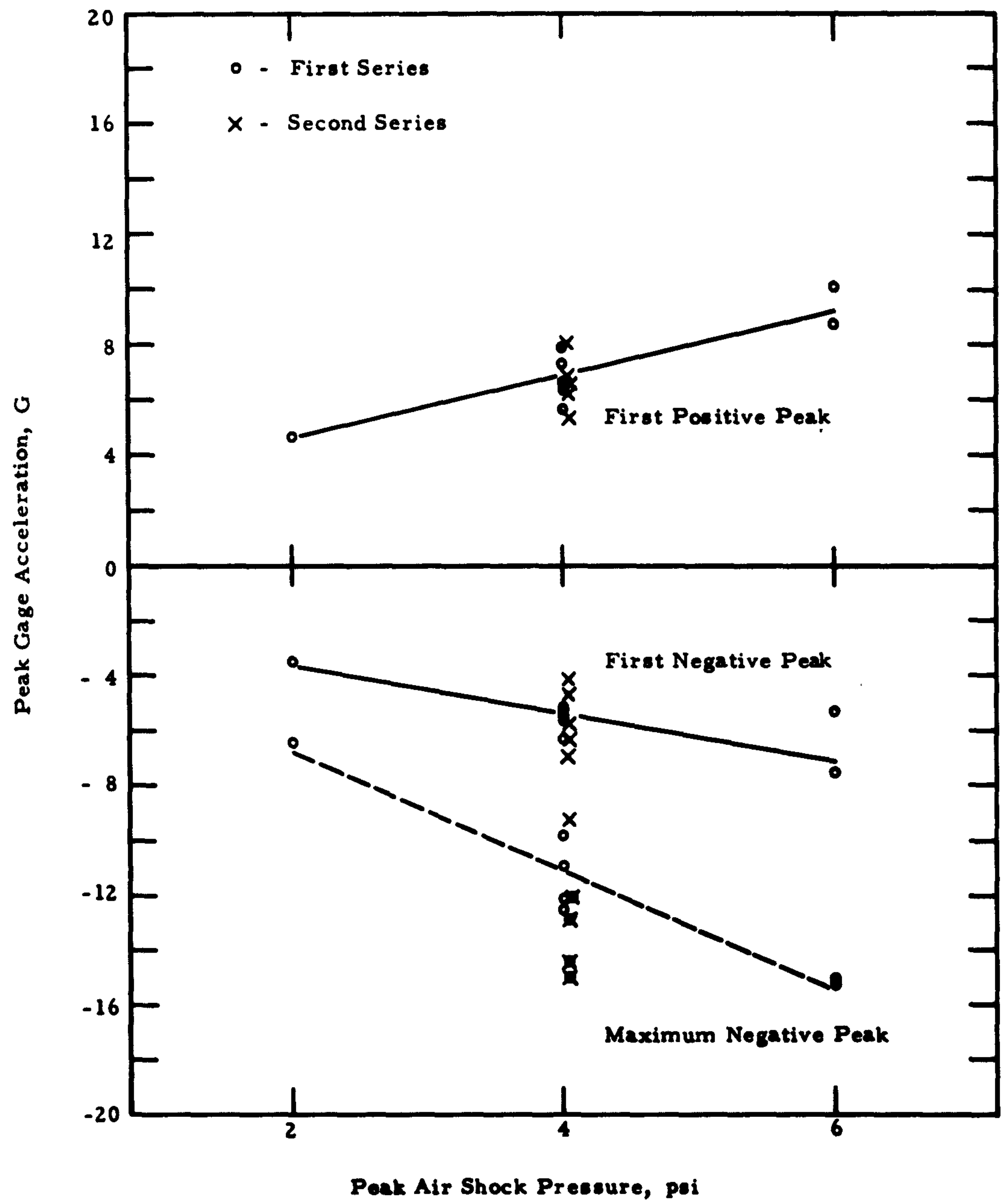


Fig. 26 RESPONSE OF ALUMINUM ACCELEROMETER TO SHOCK LOADING WHEN EMBEDDED WITH HEAVY SOIL COMPACTION

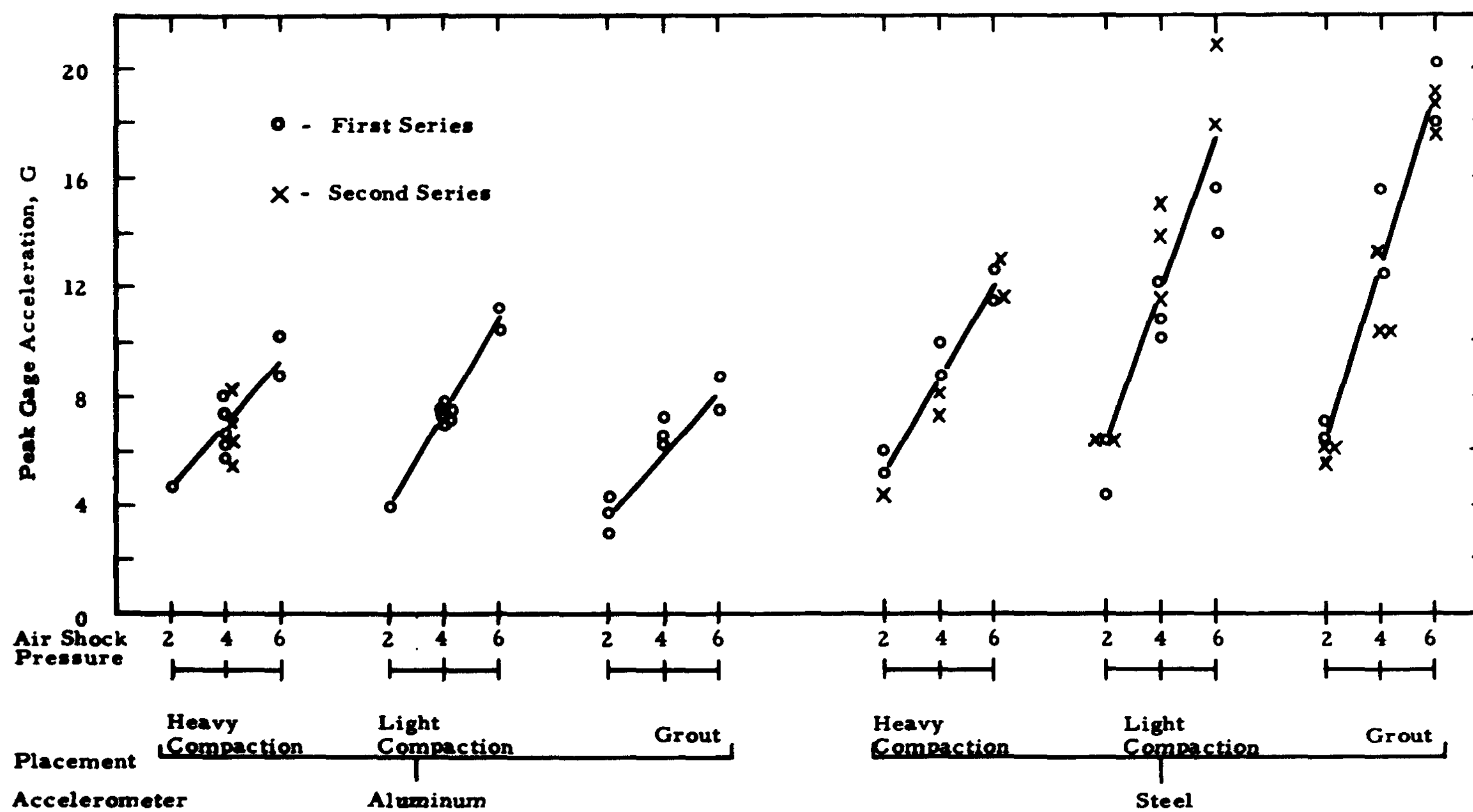


Fig. 27 SUMMARY OF FIRST POSITIVE PEAK ACCELERATIONS FOR SHOCK TUBE TESTS

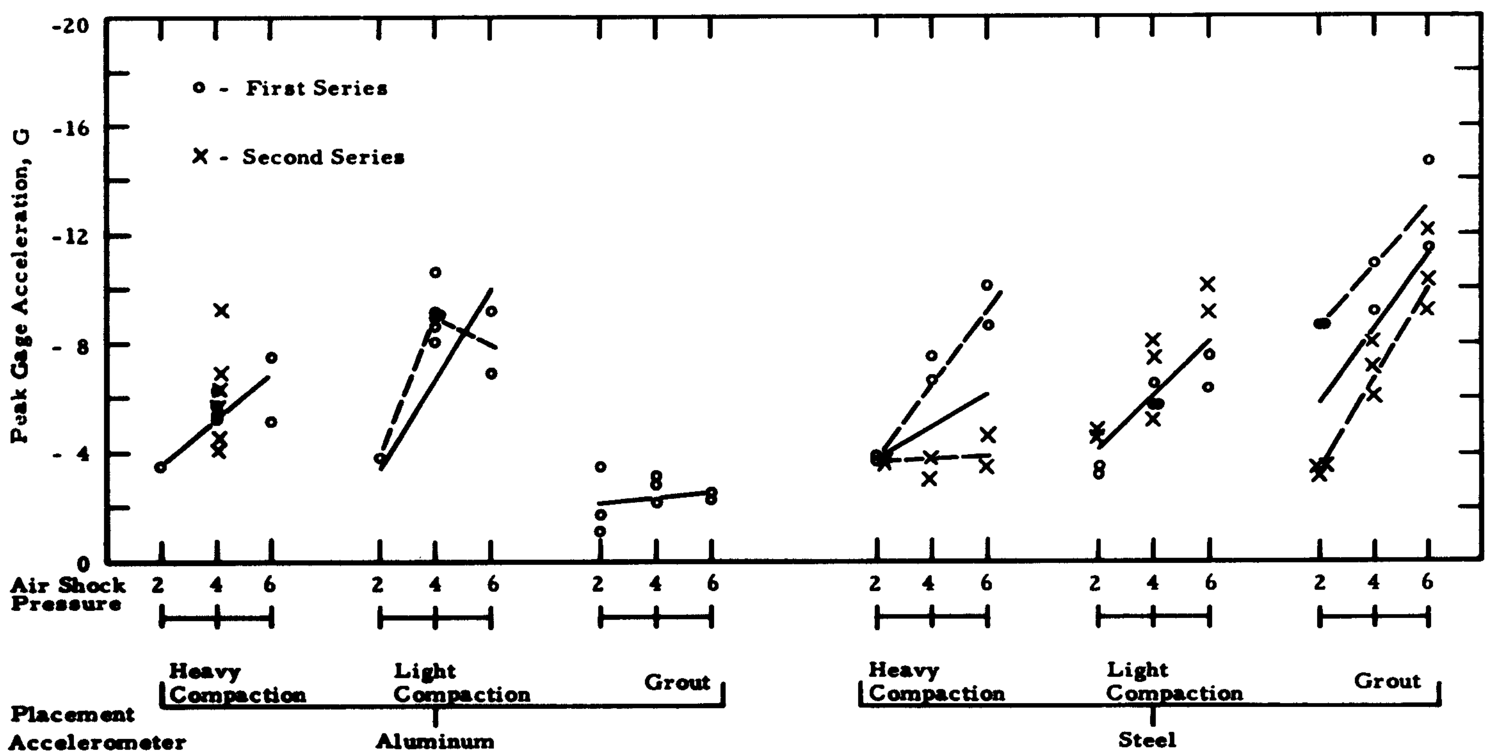


Fig. 28 SUMMARY OF FIRST NEGATIVE PEAK ACCELERATIONS FOR SHOCK TUBE TESTS

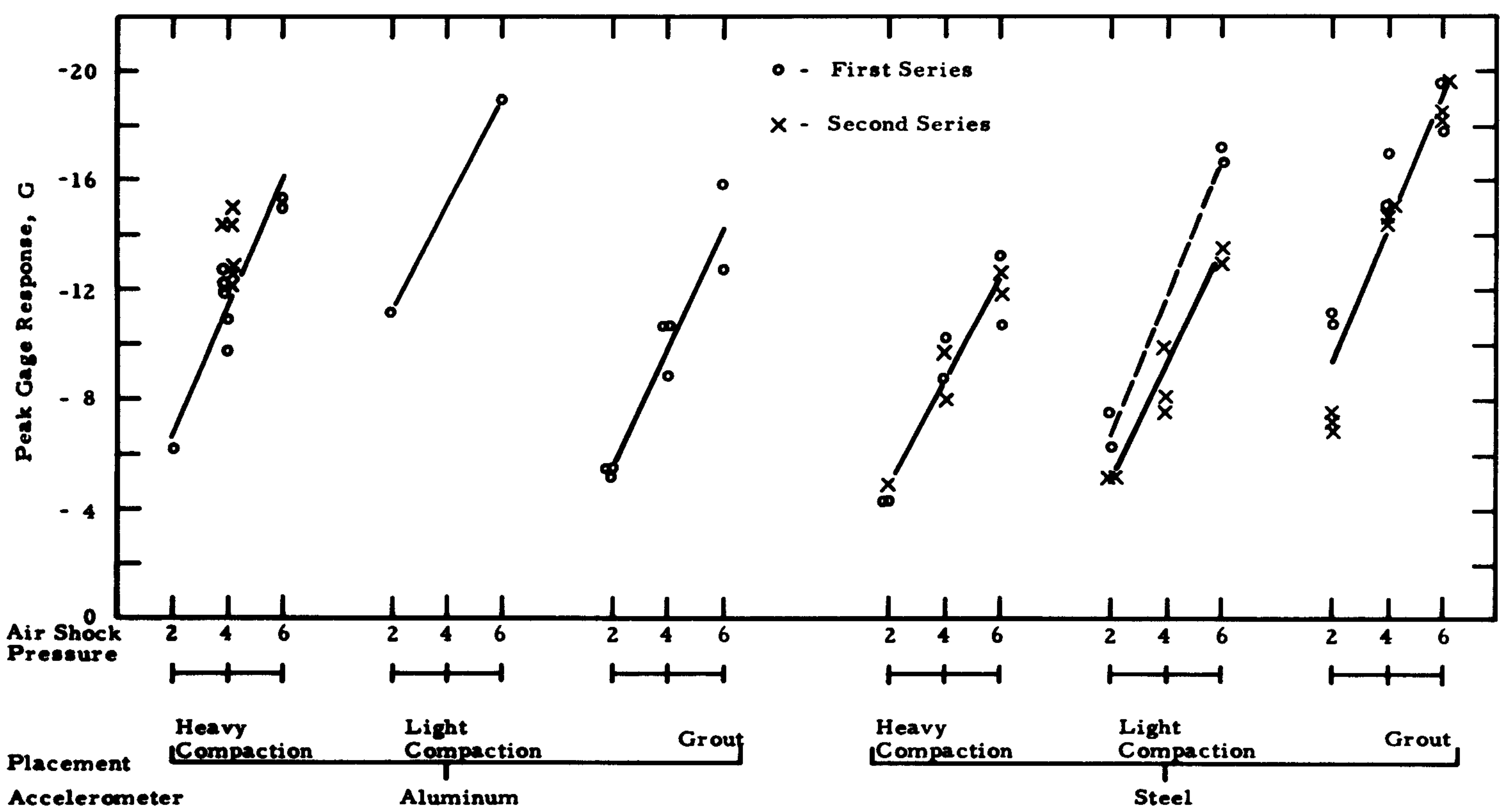


Fig. 29 SUMMARY OF MAXIMUM NEGATIVE PEAK ACCELERATIONS FOR SHOCK TUBE TESTS

accelerometer and for all applied shock pressures. The increase ranged from 0 to 57 percent, averaging 22 percent, the zero difference occurring for the lowest air shock pressures. This increase may be explained on the basis of a damped, mass-spring system as described in the pendulum studies (Figure 20). The stiffness k is less for the light compaction resulting in a lower natural frequency and hence the possibiltiy of an overshoot of the peak accelerations.

The effect of the grout appears to be inconsistent. For the aluminum accelerometer, the peak accelerations with the grout were equal to or less than the values for both maximum and minimum soil compaction. For the steel accelerometer the reverse was true. With the volume of grout used it was expected that little, if any, difference between the two accelerometer masses would be observed.

For a particular set of conditions the peak positive accelerations are less for the aluminum accelerometer than for the steel accelerometer, excluding the grout tests. The reverse is true for the peak negative accelerations. The increase in positive peaks averages 37 percent while the decrease in negative peaks averages 28 percent. The increase follows the same trend indicated in the pendulum tests although the amount is about triple. This difference may be because of the higher frequency of motion produced by the shock loading. If the peaks are viewed as oscillations about some mean acceleration then there would be an upward shift of this mean for the steel accelerometer, thus justifying the decrease in negative peaks.

As a further aid in comparing accelerometer performance, the average rate of rise of acceleration up to the first positive peak was measured. Values for 4-psi peak shock pressure are shown in Figure 30. The steel accelerometer consistently shows a greater rate of rise than the aluminum, although the difference is small for the maximum compactive effort. On the basis of the mass-spring analogy, the reverse is expected, i.e., the aluminum accelerometer should lead the steel in rate of rise. It is possible that the mass-spring analogy as stated is not the correct explanation for the observed results. Other factors, for example the difference in soil-to-metal friction on the accelerometer cases, may be influencing the behavior.

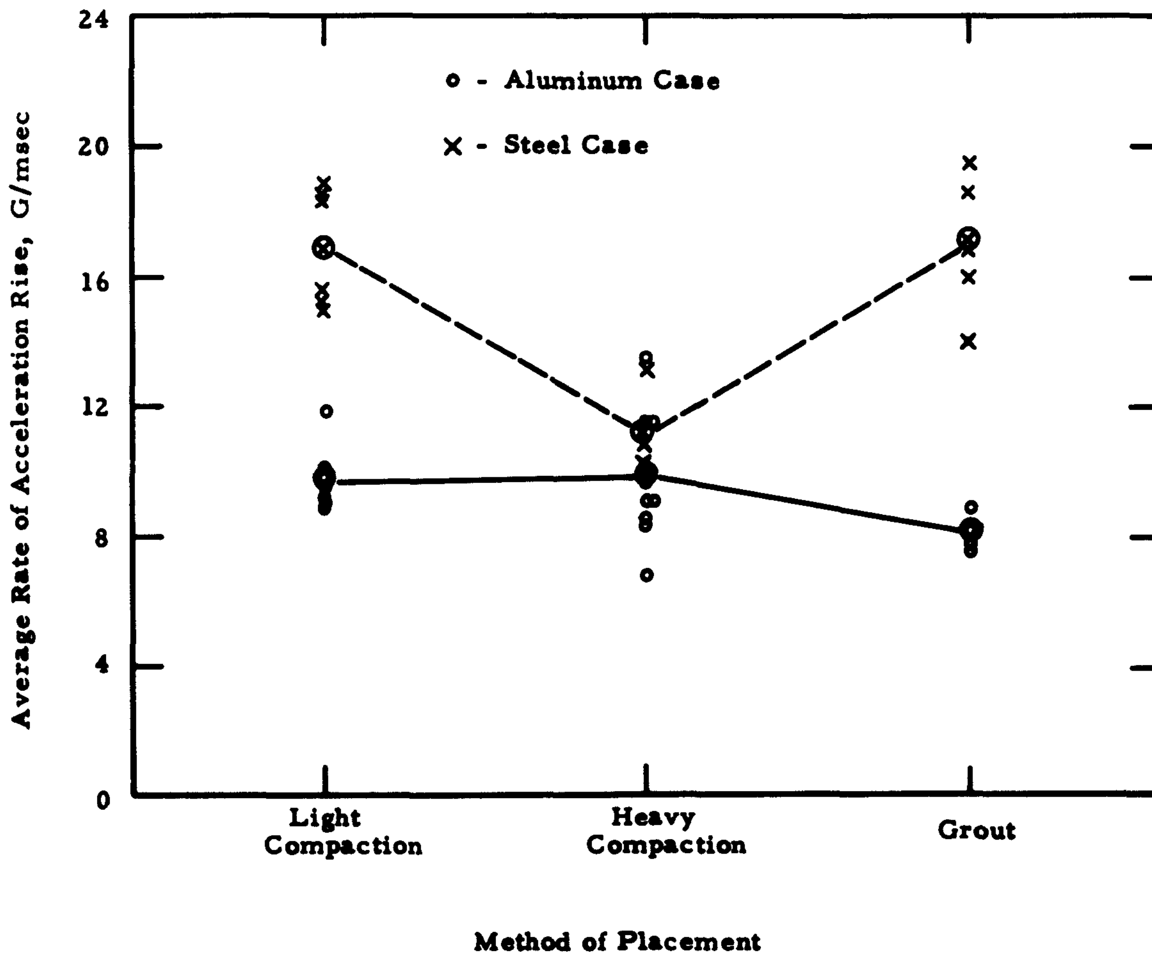


Fig. 30 AVERAGE RATE OF ACCELERATION RISE FOR SHOCK TUBE TESTS

5. RECOMMENDED FURTHER STUDIES

The experimental studies conducted on this contract have served to indicate the importance of various factors influencing the response of accelerometers buried in soil. However, much more quantitative information is needed and some questions still remain unanswered. A more detailed investigation will be required, therefore, before a suitable guide for gage placement practice can be prepared.

A more thorough examination of the effects of placement, mass, geometry, and soil conditions in general on accelerometer response should be made. Some emphasis should be placed on those important aspects which have received the least attention, for example, gage geometry, grouting and velocity measurement. In the current study little attention was given to gage geometry. This factor may not be of major significance, but such a conclusion is important and should be clearly established. Grouting is a common and very convenient method of placement which potentially could provide the best reproducibility. The results obtained with grouting in this study are inconclusive and, hence, because of the importance of this method it should be investigated further. Soil particle velocity may be both more easily measured and more useful in engineering application than acceleration. Thus, gage velocity response should be studied in the same manner as acceleration response. Lastly, a series of tests to provide more accurate estimates of the reproducibility of placement is required.

The most suitable gage for this study would be a piezoelectric accelerometer. The velocity and displacement can be obtained at the same time with electronic integrators. Although there are some instrumentation problems involved in electronic integration, this approach is feasible and will permit a direct comparison of the relative reproducibility and sensitivity of velocity and acceleration to gage placement.

Three basic types of apparatus could be used to produce a variety of motion environments: 1) shock tube, 2) impact testor, and 3) vibration table. The shock tube produces the most rapid rise of acceleration thus accentuating the effects of mass mismatch and placement. However, wave effects produce more complicated records which make it difficult to evaluate the shape of the pulse. The impact testor could provide less intense, but simple, transient soil motions by dropping confined specimens of soil containing embedded gages onto various cushioning devices. The deceleration rates could be easily made low enough to reduce wave effects. Specimens mounted on a vibration table would provide a means of evaluating the effective mass-spring response of the soil-gage system. The natural frequency, phase lag and amplification factors could all be directly observed. These studies should be conducted in a variety of cohesive soils using several placement techniques. Such studies should help to provide the basis for methods of predicting gage response.

6. CONCLUSION

Previous experience with stress, strain, and motion measurement in soil has been reviewed. The general opinion exists that stress is the most difficult measurement to make accurately, especially in the field. The most important factor influencing stress gage response is the relative stiffness between the gage and the soil. This factor is significantly affected by the placement conditions and is not a constant because the soil stiffness is variable. It is difficult to estimate the accuracy of stress measurement because so many factors influence it. However, past experience suggests that an accuracy of ± 25 per cent would be very good, in general, even with an optimum configuration and careful placement techniques.

Strain in soil is easier to measure, at least conceptually, because the gage can be designed with negligible stiffness. However, strain gages have, in general, been more difficult to place properly because of their configuration and they do constrain the soil deformations locally by their presence. For many applications, the magnitude of strains to be detected often border on the precision of the gage. For reasons such as these ±25 per cent is probably a reasonable estimate of the expected accuracy of strain measurement.

The most important factors influencing motion measurement appear to be 1) gage density in relation to the soil and 2) placement conditions. It is expected that acceleration measurements, especially peak values, are much more sensitive to these factors than velocity measurements. Placement involves either grouting or soil recompaction. For many applications, for example in a deep hole, grouting may be the only suitable method. It may also permit better reproducibility, although not necessarily better accuracy. Because grouting gave apparently inconsistent results in this study, it warrants further examination.

Reproducibility of peak acceleration measurements with the pendulum apparatus (accelerometer embedded in cylindrical specimens of dry sand) was within ±15 per cent on the average. With close control on test conditions it could be kept within ±10 per cent. Reproducibility in the shock tube experiments (gage embedded in constrained specimens of compacted clay) also averaged $\pm$ 15 percent for all placement conditions.

Two accelerometer densities were used, one about the same as that of the soil and the other about 55 percent greater. For the pendulum tests the heavier gage recorded peak accelerations averaging 12 percent greater than those for the lighter gage. For the shock tube tests, the increase was about 37 percent. The difference between these two sets of experiments may be due to the rate of loading. For placing the gages in the clay two different static compaction pressures were used, 12 psi and 42 psi. The latter resulted in a clay density about the same as that of the rest of the specimen. The peak accelerations for the smaller effort averaged 22 percent greater than those for the higher effort.

In general the reproducibility of gage response for successive identical loadings was significantly improved after the first impact for all pendulum specimens. In some cases a several hundred percent increase in gage response between the first and second impacts was observed for a relatively small change in input conditions. Because the first loading is usually of prime importance in field applications it is necessary to consider the significance of this observation. This phenomenon may likely be caused by 1) a change in specimen stiffness, which change is greatest between the first and second impacts, or 2) a change in gage coupling as a result of placement techniques. The effect was present even with very careful control on placement procedures. If the specimen change is the cause then the first and succeeding acceleration measurements may all be correct. If the cause is placement then either the first or else the remaining measurements would be in error. The answer is not now known, but the effect appears to be significantly less with cohesive soils than with sand.

It is believed that the laboratory results are a meaningful indication of expected field performance. The relationship between pulse frequency and the accelerometer-soil system frequency lie within the specimen existing in the field. The lateral constraints on the soil specimens are not the same, but this has basically no different affect on results than the normal variation in soil properties.

The purpose of the study was to provide recommendations for placement of gages in soil. The scope has been interpreted broadly because very little information is available as a basis for such recommendations and because it is necessary to obtain a perspective on the importance of gage placement with respect to the other factors influencing gage response. Intuition supplemented by field experience and the limited laboratory data available must still form the basis for judging the reliability of such soil measurements. Unfortunately it is not generally possible to obtain suitable independent checks. On the basis of accumulated experience it is quite evident that gage placement procedures have as great an influence on gage response as any other factor. Therefore, further studies of this problem are recommended.

REFERENCES

1. Wistor, J. and Perret, W. R., "Ground Motion Studies at High Incident Overpressure", Operation Plumbbob, WT-1405, June 1960, (Confidential).

2. Peattie, K. R. and Sparrow, R. W., "The Fundamental Action of Earth Pressure Cells," J. Mech. and Phys. of Solids, 2, 141-155, (1954).

3. Hamilton, J. J., "Earth Pressure Cells - Design, Calibration and Performance," Tech. Paper No. 109, Division of Building Research, National Research Council, Ottawa, Canada, November 1960.

4. "Investigations of Pressures and Deflections for Flexible Pavements," Report No. 4, Homogeneous Sand Test Section", Waterways Experiment Station, Tech. Memo. No. 3-323, December 1954.

5. "Stress Distribution in a Homogeneous Soil", Research Report No. 12-F, Highway Research Board, Washington, D. C., January 1951.

6. "Stresses under Moving Vehicles - Wheeled Vehicles in Lean and Fat Clay, 1957," Tech. Report No. 3-545, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., May 1960.

7. Bernhard, R. K., "Biaxial Stress Fields in Noncohesive Soils Subjected to Vibratory Loads," American Soc. for Testing and Materials, STP 305.

8. "Nuclear Geoplosics, Part Three - Test Sites and Instrumentation," Prepared for the Defense Atomic Support Agency by Stanford Research Institute, February 1962.

9. Perret, W. R., "Earth Stresses and Earth Strains," Operation Tumbler-Snapper, WT-503, September 15, 1962 (Confidential).

10. Perret, W. R. and Gentry, V. L., "Free Field Measurements of Earth Stress, Strain and Ground Motion," Operation Upshot-Knothole, WT-716, February 1955, (Secret, Restricted Data).

11. Goode, et al., "Soil Survey and Backfill Control in Frenchmen Flat," Waterways Experiment Station Report for Operation Plumbbob, WT-1427, November 15, 1957.

12. Mason H. and Wolfe, C. M., "A Soil Filled Soil Stress Gage," pp. 87-98, Bulletin No. 28, Part III, Shock Vibration and Associated Environments, Office of the Secretary of Defense, Research and Engineering, Washington, D. C., September 1960.

13. Mason, H., et al., "A Further Study of Stress Wave Transmission," United Research Services, Interim Report for DASA, URS-160-12, February 1963.

14. Selig, E. T. and Vey, E., "Behavior of Shock Waves in Sand," Proceedings Second Asian Regional Conference on Soil Mechanics and Foundation Engineering, Japan, I, pp. 82-87, 1963.

15. Swift, L. M., Sachs, D. C., et al., Ground Acceleration, Stress and Strain at High Incident Overpressures," SRI, Operation Plumbbob, WT-1404, May 10, 1960.

16. Swift, L. M., "Development of Soil Displacement and Strain Gages," Final Report prepared by SRI for DASA, 1961.

17. Selig, E. T., "Detection of Transient Stresses and Strains in Soil," pp. 163-190, Proceedings, Symposium on Detection of Underground Objects, Materials and Properties, Ft. Belvoir, Va., March 1962.

18. Anthony, M. V., "Ground Motion Measurements," ERDL, Project 26.3 Operation Hardtack-II, ITR-1704, February 1959.

19. Selig, E. T., Hofer, K. E. and Weil, N. A., "Elastic Response of Soil to Tracked Vehicles," pp. 97-107, Proceedings, 1st Int'l. Conf. on the Mechanics of Soil Vehicle Systems, Turin, Italy, June 1961.

20. Thornbrough, Ames and Hawk, SC-4470 (RR), Supplement to SC-4440 (RR) AEC, Final Report, Project Cowboy "Instrumentation Systems," Sandia Corp., September 1960.

21. Fischer, J. and Reisler, R., Operation Tumbler "Ground Acceleration Measurements," WT-516, January 1953.

22. Perret, W. R., Operation Redwing, "Ground-Motion Studies," May 1956.

23. Levy, S. and Kroll, W. D., "Response of Accelerometers to Transient Accelerations," J. of Research of the Natl. Bureau of Standards, 45, No. 4, October 1950.

24. Informal communications with L. Seaman of SRI, Report to be submitted to DASA, June 1963.

BIBLIOGRAPHY

Durelli, A. J. and Riley, W. F., "Performance of Embedded Pressure Gages under Static and Dynamic Loadings," American Society for Testing and Materials, STP 305.

Morris, W. E., et al., "Ground Acceleration Measurements," NOL, Operation Buster-Jangle, WT-338, June 1952 (Secret, Restricted Data).

Perret, W. R., General Report on Weapons Tests, "Ground-Motion Studies on Operation Ivy-Castle."

Perret, W. R., "Surface and Subsurface Strong Motion Measurements," Operation Hardtack-II, ITR-1703, August 10, 1959.

Salmon, L. and Hornig, S. R., Operation Tumbler, WT-517, "Earth Acceleration vs. Time and Distance," February 1953.

Swift, L. M., "Development of an Earth Velocity Gage," Final Report, SRI Project SU-2868, prepared for Defense Atomic Support Agency, under Contract DA-49-146-XZ-011, Report No. DASA-1191, October 31, 1960.

Swift, L. M. and Sachs, D. C., Operation Upshot-Knothole, WT-711, "Air Pressure and Ground Shock Measurements."

Truesdale, W. B., "Development of a Small Soil Strain Gage," Final Report for Air Force Special Weapons Center, Albuquerque, N. M., AFSWC-TR-63-3, December 1962.

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